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THE FUNCTION OF ADDITIVES IN TUNGSTEN FOR FILAMENTS

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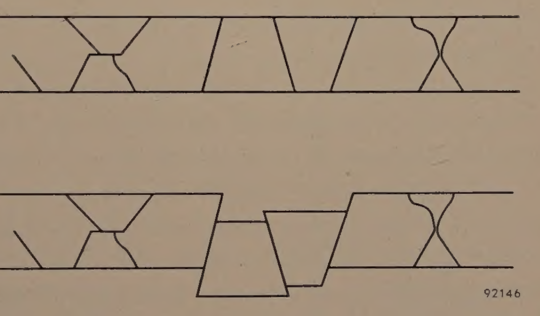
The production of coiled tungsten filaments which do not deform when incandescent is one of the most important features of modern incandescent-lamp manufacture. It was discovered some decades ago that such coils kept their shape excellently when small amounts of certain oxides were added to the tungsten at the right stage in the manufacturing process. However, even today the details of the role that these additives (dope) actually do play in the filament are still unknown. This article gives some considerations on the subject and describes a number of experiments that cast some light on the matter.

Ever since it first became possible to prepare metallic tungsten in a ductile state and to draw wire from it, the incandescent lamp industry has come to be based almost entirely on the use of this metal as its filament material. The development of processes that made this possible dates from 1909. Since then there has been only one revolutionary step in the evolution of the incandescent lamp, namely the adoption of gas-filled bulbs. At the same time coiled and coiled-coil filaments were introduced. This improvement, which was based on Langmuir's theoretical considerations (1912) and led to an appreciable improvement in the luminous efficiency [1]), at first looked as though it would come to nothing because of the behaviour of the drawn tungsten filaments.

When a coiled filament is heated to high temperature, it readily deforms under the force of gravity ("sagging"). A phenomenon which sometimes accompanies this, and is liable to detract from the shape and life of an incandescent tungsten coil, is the shearing [2]) along the boundaries of those tungsten crystals which bridge the whole diameter of the wire with relatively short boundaries ("offsetting", *fig. 1*). This article describes how these problems can be dealt with, and presents a picture (partly based on experiments conducted by the authors) of what happens during and after the drawing of the wire. We shall first, however, briefly describe how a coiled filament is manufactured.



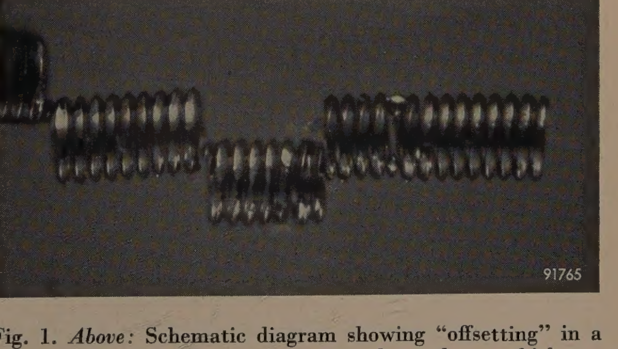


Fig. 1. *Above:* Schematic diagram showing "offsetting" in a tungsten filament along crystal boundary planes which are roughly at right-angles to the wire axis.
Below: Photograph of a coiled tungsten filament in which offsetting has occurred at various points.

[1]) Cf. W. Geiss, Philips tech. Rev. 6, 334-342, 1941.
[2]) It will be clear to the reader that the word shearing is used here in a different sense than in the study of plastic deformation and that there is no question here therefore of the sliding of a crystal along one of its glide planes.

Tungsten wire is fabricated from bars by swaging and drawing. Tungsten has a very high meltingpoint (a necessary characteristic for incandescent filaments); the bars are therefore made not by melting but by the method of powder metallurgy. A very fine metallic formed is prepared by reduction of the oxide with hydrogen. This powder is pressed into bars under an extremely high pressure (10-40 kg/mm^2). The bars are given sufficient coherence for handling by pre-sintering in a furnace. By passing a current through the bars, a temperature just short of the melting point can be reached, this taking the sintering process a good deal further (as can be seen from the increase in density and other characteristics). The bars are then strong enough to be put through a kind of forging process: the white-hot bars are swaged, i.e. machine-hammered into thinner, much longer lengths, this process also further increasing their density. The bars are now drawn into wire through hard-metal dies; wire of the smallest diameters is obtained by drawing through diamond dies [3]). When at last the wire is about 100 μ in diameter, the density is 19.2 g/cm^3 and has thus risen almost to that of the bulk metal (19.3). This wire can now be wound round a wire mandrel to form a coil. If this coil is wound, still on its mandrel core, around another mandrel, a coiled coil is obtained. By heating to incandescence, the tungsten coil becomes "set" in its new form and does not spring back when the mandrel cores are dissolved away chemically.

Owing to the strong deformation to which the metal crystals are subjected during drawing of the wire, these crystals become stretched out along the axis of the wire. These long drawn-out crystals are known as "fibres" and the fibre structure that forms is shown in *fig. 2.* When such a wire is heated to high temperature in the incandescent lamp, it recrystallizes, i.e. new crystals form in the aggregate of deformed crystals. Some control over this recrystallization is necessary if the coil is to be prevented from sagging and offsetting. When *pure* tungsten is used, fairly large numbers of new crystals form on recrystallization; such a filament soon begins to sag. Large crystals which take up almost the whole diameter of the filament, and have boundaries substantially perpendicular to the filament axis, may cause offsetting.

It might have taken years of intensive research to discover a process that led to good filaments, had not chance intervened: it was noticed that

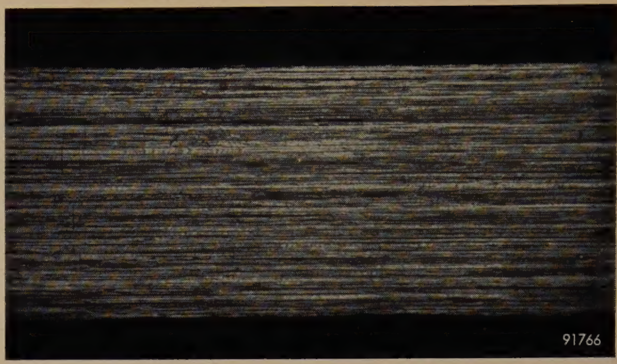


Fig. 2. The "fibre structure" of a drawn tungsten wire which has not yet recrystallized. Magnification 265 ×.

tungsten exhibited particularly good non-sag properties in the recrystallized filament or coil, if the metal had been prepared from raw material (WO_3) which had been heated in a Battersea crucible [4]). It turned out that an extremely small amount of the material of the crucible found its way into the tungsten oxide, and that the active components of the contaminant were the oxides K_2O, Al_2O_3 and SiO_2. Addition of these substances to the tungsten at the appropriate stage in its manufacture, was found to result, during recrystallization, in the formation of longer boundaries between the various crystals; moreover, these boundaries made, in general, smaller angles with the wire axis, often assuming sharp arrow-head shapes (*fig. 3*). This remarkable effect is far from being the only influence that the additives ("dope") have on the properties of tungsten wires. A discussion of these effects and of the innumerable experiments that have been carried out in this field would fill a book, however. We shall confine ourselves therefore to examining the long, arrow-shaped boundaries which evidently prevent sagging and offsetting; we shall also put forward an explanation of the effect of the additives on the formation of the crystal boundaries.

Before going any further it should be remarked that the additives, which are added to the WO_3 in small amounts (a few per cent by weight), largely disappear during the subsequent manufacturing process. Only about 0.01% of Si and Al can still be detected in the filament as it goes into the lamp. Nevertheless these very small amounts appear to be adequate to influence recrystallization in the desired manner.

[3]) Cf. J. D. Fast, Philips tech. Rev. 4, 309-316, 1939.

[4]) This was a type of crucible of Al_2O_3-rich earthenware made by the firm "Battersea" and formerly much used in chemical plants and laboratories.

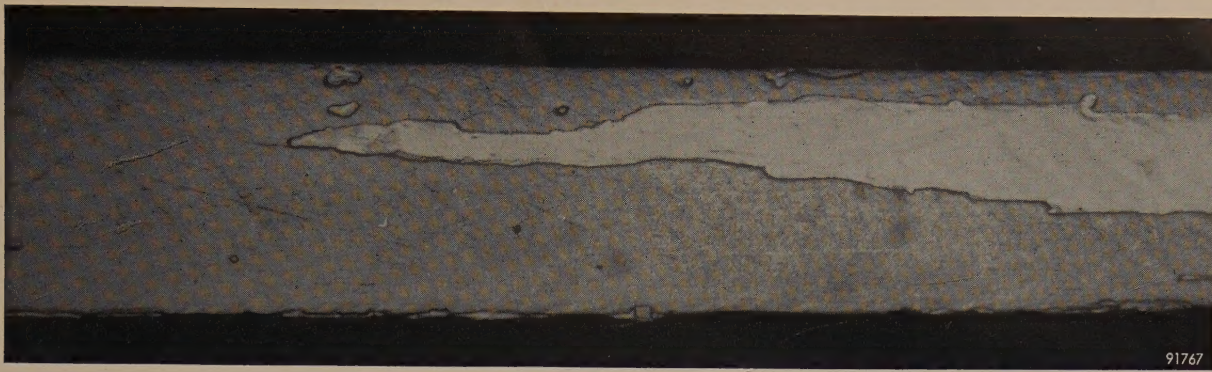


Fig. 3. Arrow-shaped boundary between two crystals in a recrystallized tungsten wire. Magnification 200×.

The form in which the additives are present and their influence upon the recrystallization process

According to present ideas, the substances added are thought to form compounds (e.g. potassium silicotungstates, or perhaps tungsten bronzes) which are fairly stable, possible survive the reduction process and do not completely evaporate at the high sintering temperature. These compounds, or what is left of them in the form of decomposition products, are present as impurities that are not soluble in the tungsten, but form a separate phase. It is plausible to assume that these slag-like impurities are spread out — like the metal itself — along the wire during the drawing process, and that they occur in the wire along lines or planes or as tubules. We shall now describe a number of model tests which illustrate how such fibrous and tube-shaped structures can make for the formation of the desirable long crystal boundaries [5]).

Model tests

Let us imagine a length of wire containing impurities in tubular form, i.e. we picture the wire as a bundle of thin-walled tubules, the wall of each tube being made up of the residues of the additives and the space between them consisting of fine-grained tungsten. Owing to the irregular manner in which the tubules arise, they will be blocked here and there by cross-walls (dams), while at other places there will be holes (leaks) in the walls. In the actual wire the situation will be rather more involved, but will in principle be the same.

Let us now assume that somewhere in the "tungsten" part, the nucleus of a new crystal forms and begins to grow. In the tubule in which it is contained, the crystal nucleus grows unhindered to form a small crystal, but at the walls and dams in the tubule its growth is impeded. However, the crystal can grow out through a leak in the wall into the adjacent tubule and can expand throughout the whole of that tubule up to the dams; it may then grow further through leaks in this tubule.

Minor holes in the walls may nevertheless not act as leaks: owing to crystal-boundary energies, it is only fairly large leaks that will be passable (cf. a liquid with a high surface tension that does not leak from a porous vessel). Also, a row of pores can have an impeding effect just as a row of foreign particles.

If we restrict our representation to two dimensions, we can imitate what happens by constructing a simple model as follows. A large number of parallel lines, representing the tubule walls in the wire, is drawn on a sheet of paper. At random, dams are drawn in indicating where the tubes run to a dead end, and leaks are inserted by interrupting the long lines at various places. In the first series of experiments, we make the number of dams and leaks equal; in subsequent series of experiments we can take unequal numbers of dams and leaks.

With such a diagram we can perform the following "recrystallization" experiments. We create a crystal nucleus at each of two places and allow them to grow along the tubules and through the leaks according to certain rules. Each nucleus is permitted to advance a certain amount in turn: just how far is laid down by "rules", which may be different for each group of experiments. Thus, for example, we can allow each crystal in turn to fill up completely the section of tubule in which it started; it then has to wait until its next turn before it can occupy a neighbouring tubule via a leak. This corresponds to the assumption that the passage through a leak takes a relatively long time. Another possibility is that the crystals are allowed to grow at a constant rate. Still other possibilities, of course, exist. *Fig. 4a* shows a "crystal" in course of growth according to the first-mentioned of these rules.

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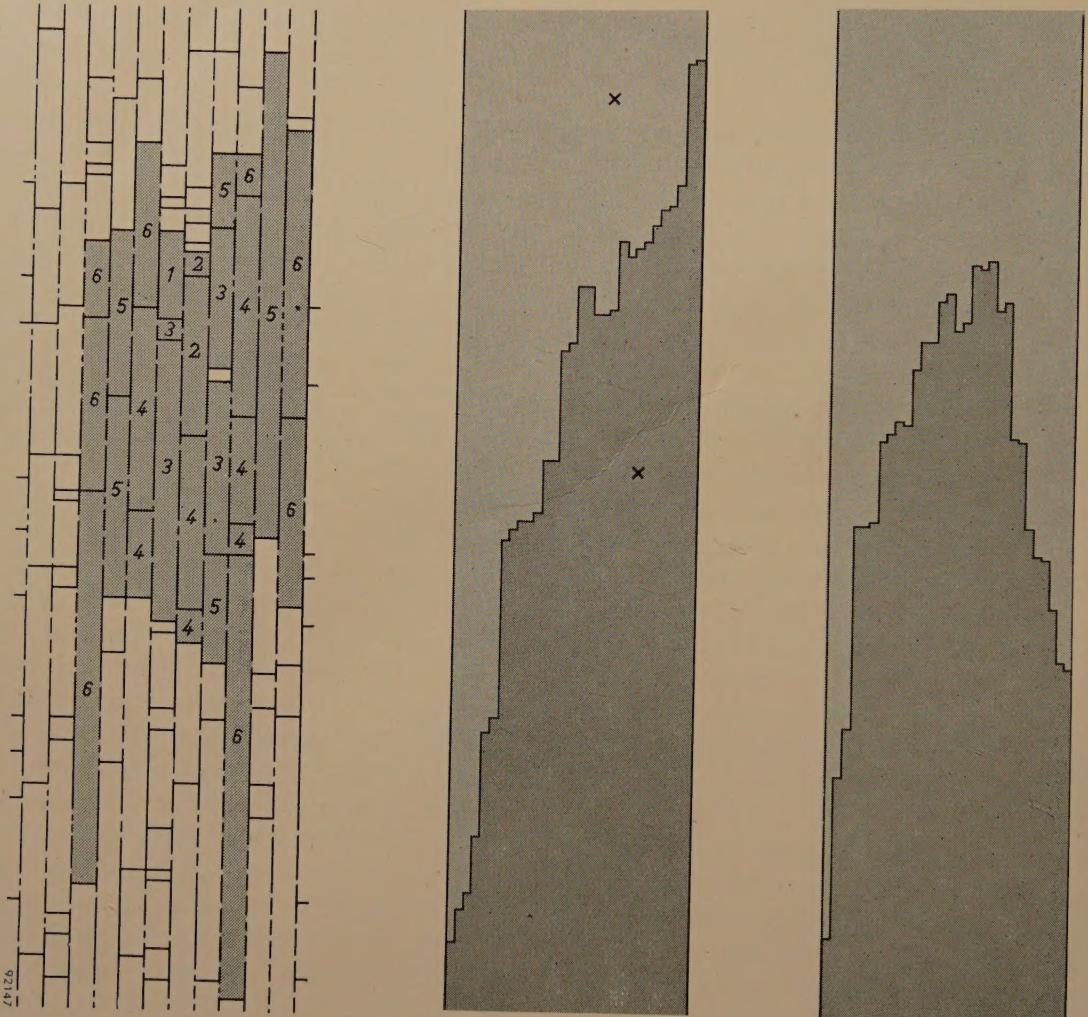
[5]) J. L. Meijering, Modellversuche über das Entstehen des Stapeldrahtgefüges in Wolfram, published in Warmfeste und korrosionsbeständige Sinterwerkstoffe, 2. Plansee-Seminar 1955, Reutte/Tirol, pp. 305-312 (published 1956).

Two crystals growing in such a manner will finally meet at one or other boundary line. It is interesting that these boundary lines show a strong similarity to the crystal boundaries that occur during the recrystallization of tungsten filaments prepared from "doped" tungsten. The long boundaries making a small angle with the longitudinal axis of the wire, and the arrow-shaped boundary lines can be recognized. Figs. 4*b* and 4*c* are examples of the results obtained in this "recrystallization on paper". By varying the number of leaks, dams and crystal nuclei present per unit area, structures can be obtained which resemble the recrystallization patterns of both the doped wires (long crystal boundaries) and the pure metal wires (roughly equidimensional crystals). According to these paper-model experiments not only the boundary between two new crystals, but also that between a crystal and



a *b* *c*

Fig. 4. Paper-model experiments on the recrystallization of tungsten wire. The system of strands and tubules running lengthwise along the wire and made up of foreign particles assumed to be present in the wire, is represented in two dimensions by a system of vertical parallel lines, two typewriter spaces apart. Here and there these lines are broken ("leaks"), in other places lines across the tubes indicate blockages ("dams"). These were marked at random in our experiments with the aid of a typewriter and a table of random numbers, such as can be found for example by throwing a die or by any other system in which chance is decisive. We proceed as follows: reading through the list of random numbers, we type a mark on the page of vertical lines whenever a certain number, say 2, occurs. For all other numbers we strike the spacer. If we are *between* two lines, the mark made is a dash (—) and in this way we get a "dam". If we are *on* a line, we strike another character (e.g. =) which represents a leak at that point. (This gives approximately equal numbers of leaks and dams; it is easy to modify the "rules" so as to give other ratios of leaks to dams.) In the experiments crystals were permitted to nucleate at two random points in the diagram, each crystal being allowed "to make a move" in turn.
a) The growth of one such crystal. Each turn the crystal is allowed to occupy a complete section of tubule. The numbers indicate which parts of the tubules were filled in a particular turn. The shaded area indicates the shape of the crystal after six turns. In this model there were twice as many leaks as dams.
b) Oblique boundary between two crystals, as frequently found in these experiments. The two crystals grew from the points marked ×.
c) Arrow-shaped boundary. The crystal nuclei were situated at points outside the figure.

the fibre structure that has not yet recrystallized are of the "long boundary" type. This is in accord with what is actually observed when a crystal runs to a dead end in the fibre structure. Such a situation can arise for example when the temperature is just below the recrystallization temperature, rising above it only in a part of the wire. This is easily achieved by slightly etching away part of the wire, so that the current density is not everywhere the same (*fig.* 5). When a specimen of such a wire is viewed under powerful magnification, a stepwise pattern can be seen where the crystal growth into the "fibres" has halted.

This demonstrates how impurities can inhibit the growth of the crystals — in particular, growth at right-angles to the wire axis mainly owing to the fact that the impurities are stretched out along the wire — and in this way promote the formation of long crystal boundaries. It will be obvious that it is chiefly the least volatile of the additives, such as SiO_2 and Al_2O_3 or their compounds, that exercise this function.

The structure of the recrystallized tungsten wire

We have contended that it is highly probable that the residues of the additives are present in the drawn wire as elongated strands which exert a strong influence on the recrystallization of this wire. This view is confirmed by a second series of experiments, now to be described, which show that the additives are still present in the form of tubules or strands when the recrystallization process is over [6]).

The structure of the wire was investigated by making Laue diffraction photographs, using a very narrow beam. The latter was obtained by means of a 2 cm long lead-glass collimating capillary of about 50 μ bore. With this arrangement very small differences in orientation between crystallites can be detected. The very small diameter of the X-ray beam makes for a high resolving power (about one minute of arc); moreover the irradiated spot is so small that it covers only a few crystallites. *Fig. 6a* shows a Laue photograph (taken with a normal beam, not specially narrow) of a crystal of rock-salt orientated arbitrarily with respect to the X-ray beam. Fig. 6*b* shows how such a photograph appears when the beam falls on two crystals having a small angle with respect to each other (doubling of Laue spots).

[6]) G. D. Rieck, Fragmentation in tungsten crystals, Acta metallurgica 4, 47-51, 1956 (No. 1).

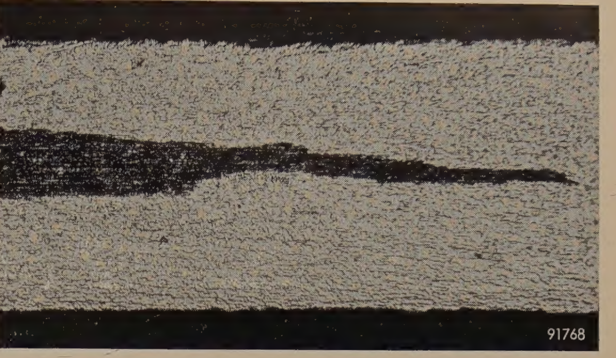


Fig. 5. Photograph of the boundary between a new crystal and an unrecrystallized region of the wire (the fibre structure). The required temperature gradient was obtained by slightly etching away part of the wire. The darker region in the photograph is the original fibre structure, the lighter region is recrystallized metal. Magnification 160×.

If back-reflection photographs are made of recrystallized tungsten wires at places where the whole cross-section is taken up by only one crystal, it is often found that one spot in the diagram obtained is split into two or more smaller spots. More than half the crystals examined were found to exhibit this splitting of the spots, and it was noteworthy that this splitting usually corresponded to rotation about an axis *parallel* to the wire axis. *Fig. 7* shows a few examples of parts of such diagrams [7]). From the distance between the spots, the angle between the irradiated crystallites can be calculated. Angles of about 2′-30′ are commonly found. From the surface area irradiated and the number of spots found, moreover, it is possible to make an estimate of the size of the crystallites involved. The diameter found varies from 20 to 70 μ.

It may be remarked at this stage that the axial rotation of the crystallites with respect to each other fits in well with the hypothesis of strands or walls of impurities running parallel to the wire axis, and with the picture of recrystallization that has just been discussed. For it is reasonable to expect that the parts of a crystal on either side of a wall will often show small differences in orientation. The two parts of the crystal will be in contact only at one point, namely at the leak from which the second part began its growth. The geometry of the wire then lends greatest probability to a difference in orientation corresponding to rotation about the wire axis, in accord with the rotational symmetry of the fibre structure of the wire.

[7]) Splitting of the spots also occurs as a result of trivial effects, viz. 1) if the X-ray beam strikes the film at an angle and the film has emulsion on both sides; on developing the film two spots appear, on the front and back of the film, which do not coincide; and 2) if the lead-glass capillary is not sufficiently narrow, so that the local differences in brightness of the anode are manifested in each spot.

a

b

Fig. 6. A Laue photograph of NaCl. When white X-rays (continuous spectrum) fall upon a crystal, the various planes in the crystal occupied by atoms or ions diffract this radiation. The pattern which is formed with a given angle of incidence of the X-ray beam, is determined by the position of the various lattice planes in the crystal. Laue diagrams can be made either with small angles between the incident and reflected beams, the film being mounted behind the crystal (transmission photograph), or with large angles, the film being mounted in front of the crystal (back-reflection photograph). In the latter case the film has an aperture to let through the incident X-ray beam.
a) Back-reflection Laue pattern of a single crystal. *b*) Back-reflection Laue diagram of two crystals which are turned through a small angle with respect to each other. (These photographs were not made with a very fine beam.)

Bending test

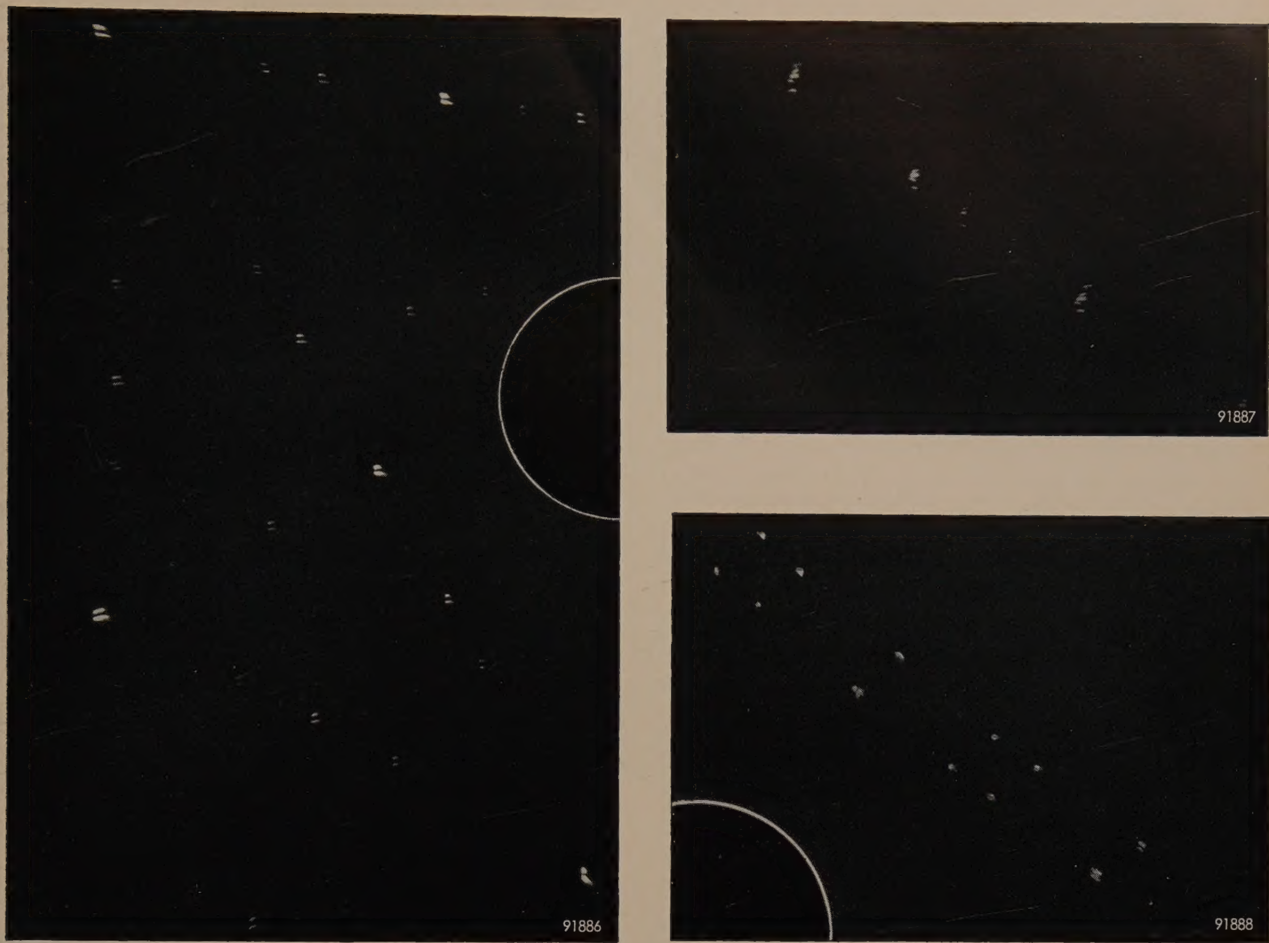
The wires containing the crystallites just discussed were fixed horizontally on a specimen holder, at right-angles to the X-ray beam. The following experiment was then performed on these wires. They were bent through an angle of 90°, in a plane at right-angles to the X-ray beam, with a radius of curvature of (for example) 2 mm (the diameter of the wire was 180 μ). The wires were then straightened as far as possible. The experimental set-up made it possible to ensure that the X-ray beam impinged on exactly the same spot in the previously examined part of the wire, which was also the middle of the bent region.

As is well known, a deformed crystal gives a Laue diagram with elongated spots (asterism) [8]). The direction in which the spots are elongated is related to the direction in which the lattice plane in question is curved. When the tungsten crystals were bent back, this asterism was found largely to disappear as far as the spot elongation parallel to the axis of the wire was concerned; the spots were usually little changed in a horizontal direction after the experiments. In the vertical direction, however, something had happened. Spots that had displayed some degree of splitting earlier, were more decidedly split, and in spots where no splitting had previously been observed, this was frequently found after the bending test. The angular differences were again of the order of a few minutes, but the number of spots was often bigger, corresponding to particles of about 7 μ diameter. The phenomenon that the effect of bending was more persistent in the "vertical" than in the "horizontal" direction can now be explained on the assumption that strands of impurities are present in the crystal investigated. The explanation is in terms of lattice defects (dislocations) that arise as a result of deformation [9]).

When a substance is bent plastically, edge dislocations are formed. An edge dislocation can be imagined as being caused by the presence of an extra atomic half-plane, in this case inserted into the crystal lattice from the outside of the bend

[8]) See, for example, W. G. Burgers, Philips tech. Rev. 5, 157-166, 1940.

[9]) See, for example, Philips tech. Rev. 15, 246 and 286, 1953/54.



a b c

Fig. 7. Laue photographs of recrystallized tungsten wires. A splitting of the spots is observed, this being due to small differences in the orientation of the crystallites: *a*) two-fold splitting (three times actual size); *b*) five-fold splitting (four and a half times actual size); *c*) the spots in this photograph originate from two crystals which are at an angle of 2° and are each separately re-split (three times actual size).

(*fig. 8*). If the wire is now bent in the opposite direction, dislocations are produced which can be thought of as resulting from extra atomic half-planes inserted from the opposite side of the crystal. The extra half-planes of these two kinds may often compensate each other, provided the mobility of the dislocations is sufficiently great. The mobility of a dislocation is markedly reduced if the edge of the extra atomic half-plane, i.e. the dislocation axis, comes up against some foreign atoms (impurities) in the crystal lattice. If the dislocation axis coincides with a *row* of foreign atoms, then the dislocation may be rendered immobile and no longer able to combine with an opposing dislocation (which in its turn may also be locked against another, parallel row of foreign atoms). However, dislocations whose axes are at right-angles to such rows of impurities will be practically unimpeded.

We have seen that in the tungsten crystal the

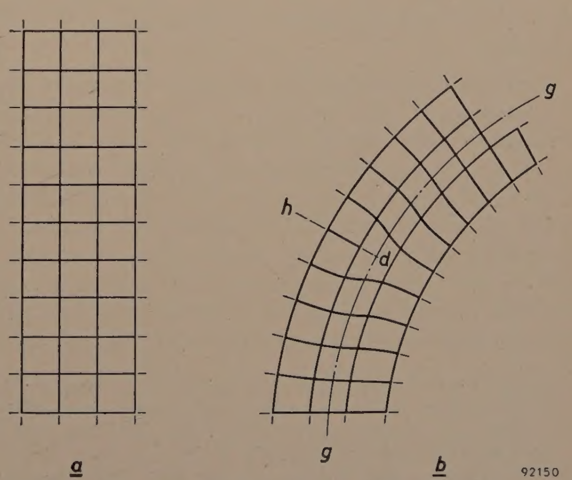


Fig. 8. Schematic diagram of part of a crystal lattice in which shearing has occurred as a result of bending, so that an edge dislocation has formed. *a*) The lattice prior to bending. *b*) The same section of the lattice after bending. Shearing has occurred along the glide plane *g*; this is equivalent to the insertion of an extra half-plane of atoms at *h*. The edge of this plane, i.e. the line at right-angles to the plane of the drawing through the point *d*, is the dislocation axis.

changes in the spots resulting from deformation purely in the plane of the bent wire (as in fig. 8), are restored to normal when the wire is bent back. The corresponding dislocation lines are then at right-angles to the axis of the wire and there is evidently nothing to impede their mobility. However, the (secondary) deformation corresponding to the change in the shape of the cross-section on bending the wire, which manifests itself in a splitting of the spots in a direction at right-angles to the wire (see fig. 7), does not disappear. The dislocations corresponding to this deformation are mainly parallel to the wire axis and evidently they are partly blocked. As we have seen, such a locking of these dislocations is to be expected where there are rows of foreign atoms likewise running parallel to the axis of the wire. This is thus in very good agreement with the view that there are still traces of impurities present in the recrystallized tungsten crystals in the wire, these impurities being arranged in lines parallel to the wire axis.

The rows of foreign particles need not, of course, be one atom thick; to explain the difference in mobility of both types of dislocations, it is sufficient to assume that these particles are distributed more extensively along the axis of the wire than at right-angles to it.

We thus find confirmation for the picture of the impurity distribution obtained from the experiments with paper models, which gave an acceptable explanation of the way in which long and arrow-shaped boundaries can arise between the crystals in a tungsten filament.

Other conceivable explanations of the occurrence of long boundaries

When two crystals grow, for example in a piece of metal, at a certain moment they will meet. It is then possible that one of the two crystals will continue to grow at the expense of the other [10]); alternatively they may maintain one common boundary. In general it can be said that when the boundary-surface energy is low, there is little tendency for the boundary to move by the growth of one crystal at the expense of the other. In such a case the boundary can in general be a long one (since its total energy will then still be low). Such a long boundary could for example occur between twinned crystals [11]). Also, crystals which have almost the same orientation, can easily exist side by side and may possess long crystal boundaries.

It might be that the crystals having long boundaries in tungsten wires are in one or other of the two relationships described above. It is of course *a priori* improbable that two crystals which nucleate some distance apart and grow towards each other, would possess a twin-crystal relationship, but it can well be imagined that such a relationship might occur if one of the two crystals were to arise from a nucleus that was formed on the growth front of the other. Disregarding special orientations it is further not unreasonable to suppose that such a crystal on the growth front of another, would locally affect the growth of the latter and by so doing contribute to the formation of a curiously shaped boundary; such a situation has actually been found in aluminium [12]).

X-ray diffraction patterns showed, however, that the angles between tungsten crystals with long boundaries can have various values; also, tungsten crystals bordering on each other were not usually found to have a twin relationship, though twinned crystals might under some circumstances occasionally occur.

We have investigated in the following manner whether two crystals which grow towards each other and are thus unable to influence each other, are able to form a "long" boundary.

"Shunt" experiments

It is possible to make a crystal boundary such that it is certain that the two bordering crystals are nucleated in the fibre structure at least $1^1/_2$ cm apart. This has been done as follows. The wire (in these experiments of diameter about 0.3 mm) is fitted with a sleeve ("shunt") of length, say, 15 mm (see *fig. 9*) between the points A and B. The "shunt" consists of six pieces of the same wire as that under test, cut to this length, and positioned around the wire; they are held in place by means

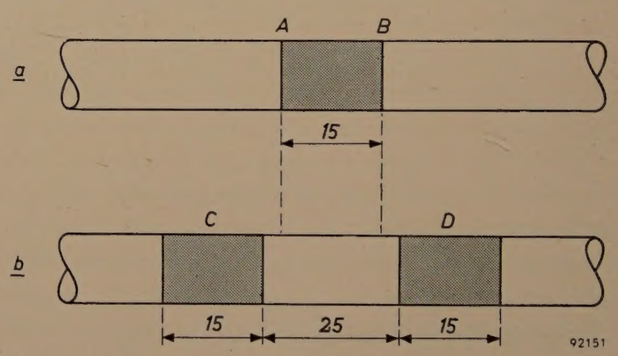


Fig. 9. Schematic diagram of the recrystallization experiments designed to obtain crystal boundaries with the certainty that the crystals involved had been nucleated far apart from each other. A sleeve ("shunt") was fixed around the wire. Within the shunt the wire is less strongly heated, so that recrystallization cannot occur there. The dimensions are given in mm. The "cold" sections are shaded in.
a) In the first heating the shunt envelopes the section AB. Crystals originating from the left or right cannot grow into the region AB.
b) In the second heating two shunts are mounted. The crystals whose growth was halted at A or B can now continue their growth. If crystals are found whose one extremity lies in AB and whose other extremity is beyond C or D, it is certain that these crystals have nucleated *outside* the section AB in the first heating. As a rule only one crystal boundary is found in the section AB, this being of the same type as those found after recrystallization under normal circumstances.

[10]) In the case of iron alloys this phenomenon has actually been followed, as it occurred, under an emission electron microscope, cf. Philips tech. Rev. **16**, 337-339, 1954/55, and **18**, 1-10, 1956/57 (No. 1).

[11]) A twinned crystal consists of two parts which are in a certain symmetry relationship to each other: they are either mirror images of each other with regard to a common lattice plane, or they are turned through 180° with respect to each other about a two-fold axis of symmetry (both features may be present at once). The mirror plane usually has simple indices and is *not* one of the planes of symmetry of the crystal structure. In general it does not coincide with the interface, which need not be flat.

[12]) W. G. Burgers, Physica **9**, 987-995, 1942.

of a piece of thin wire wound round them. The shunted wire is mounted stretched and vertical in a tube through which hydrogen is passed. On heating the central wire to about 2250 °C by passing a current through it, the shunted section does not rise above 1000 °C and therefore does not recrystallize. After fifteen minutes, the wire is cooled and is then heated with *two* shunts (C and D in fig. 9). Finally, a longitudinal section is prepared for microscopic examination.

As a rule one crystal boundary is found in the section AB which represents the boundary between the crystals that were halted at A and B by the "cold" section AB during the first heating. If the one crystal extends to the left of C and the other to the right of D, we can be *certain* that they were formed left of A and right of B during the first heating, since the two "protective" shunts used in the second heating prevent any crystal that might nucleate between A and B (e.g. on the growth front of the "left-hand" crystal) from growing out to the right beyond D, swallowing up another crystal.

Complications can arise; for example a third crystal may form in AB or may already be present next to one of the two other crystals at A or B. But on various occasions there was only one boundary between C and D, and this was always of the same type as is found when a filament is heated to incandescence in the normal way. Nor were any twinned crystals found. In a few instances the second heating was extended to 10 hours at 2400 °C. This did not lead to different results, so that the boundaries evidently possess an appreciable stability.

From all this it must therefore be concluded that the simple orientation relationship postulated above does not exist. However, this does not mean that some orientation relationship does not exist. Even after recrystallization there is a preferred crystallographic axis parallel to the wire direction. But the crystals can be turned through any possible angle with respect to each other, about this axis. [13])

[13]) This will be discussed at greater length in an article to be published elsewhere.

The experiments also demonstrate that the long or arrow-shaped boundaries found cannot be explained by the growth of a crystal nucleus on the boundary between the recrystallized region and the fibre structure. On the contrary, the actual growth front (between a crystal and the fibre structure) is found to be irregular and capable of assuming the arrow shape (fig. 5).

Summary. Tungsten wire for the filaments of incandescent lamps is made from sintered tungsten bars by swaging and drawing. In this process the crystals are deformed and a fibre structure is produced. If a wire is heated to incandescence, recrystallization occurs and crystals are formed that are larger than those previously present. If such a wire is now to be suitable for use as a coiled filament, it must not sag or show offsetting. Some decades ago it was found that these effects can be avoided by adding certain substances (dope) at an early stage in the production of the wire. Long crystal boundaries are then formed during recrystallization.

With the aid of two-dimensional diagram experiments a plausible explanation is given of how the formation of long crystal boundaries is promoted by the presence of foreign particles arranged in the wire in the form of strands or tubules. A system of tubules were drawn on paper and leaks and stoppages introduced in them in a purely random manner. Two "crystals" are made to grow and fill the system of tubules, starting from two points in that system, and following certain rules. X-ray diffraction patterns of crystals in recrystallized wires confirm the picture obtained. If a crystal is bent and then straightened, the dislocations of opposite sign can compensate each other when their axes are at right-angles to the axis of the wire, but not when they are parallel to the axis of the wire. The foreign particles forming the tubules are identified with the residues of the dope stretched out along the wire during drawing.

Experiments in which unrecrystallized tungsten wires are locally heated to high temperature show that the long or arrow-shaped boundaries between tungsten crystals cannot be explained in terms of twinned crystals, nor in terms of re-nucleation (with random orientation) on the recrystallization front.

A TRANSMITTING TRIODE FOR FREQUENCIES UP TO 900 Mc/s

by P. J. PAPENHUIJZEN. 621.385.3.029.6:621.3.032.213.1

*New designs have made it possible to use triodes as amplifiers or oscillators at unprecedentedly high frequencies. This was recently illustrated by an article in this Review on the EC 57 disc-seal triode *), which delivers a power of several watts at 4000 Mc/s. Considerable progress has also been made with triodes for appreciably higher power ratings. The transmitting tube TBL 2/300 discussed in the present article — also a disc-seal triode, but with a cylindrical electrode system as opposed to the planar electrodes of the EC 57 — has an output of about 400 W at 470 Mc/s and about 150 W at 900 Mc/s. It meets a need that has become increasingly pressing of late.*

In recent years the frequency range from about 450 to 900 Mc/s (wavelengths from some 7 to 3 dm) has come more and more into prominence. To give only a few examples, decimetric waves have acquired great significance in aviation for the purposes of communication and navigation; mobilophone communications at frequencies between 460 and 470 Mc/s are growing rapidly in number; in television more and more interest is being shown in bands 4 and 5 (470-585 and 610-960 Mc/s); high-frequency heating with dm waves is steadily gaining ground in industry; and in Germany a frequency range in the neighbourhood of 461 Mc/s has recently been reserved for diathermy, in connection with investigations being carried out into the therapeutic value of dm waves. In addition, numerous military applications might be mentioned.

Triodes of conventional construction are, for various reasons, unsuitable for decimetric waves. If we attempted to use such tubes at such wavelengths we should find in the first place that the electron transit time — the time taken by the electrons to travel from cathode to anode — would be too long in relation to the period of the oscillation to be generated or amplified. In the second place, the wavelength would no longer be large compared with the length of the electrodes, so that the voltages at different points of the same electrode would show phase differences; this effect becomes noticeable as soon as the wavelength drops to about 10 times the effective electrode-length. In the third place, at frequencies of several hundred Mc/s the dielectric losses in the insulating parts of the tube would be considerable, and finally, the self-inductance of the lead-in wires would exercise an adverse influence [1]). These four effects (transit-time effect, phase shift along the electrodes, dielectric losses and stray self-inductance) are, as regards transmitting triodes, the main reasons for the loss of efficiency at higher frequencies; at a certain limiting frequency the efficiency finally becomes too low for the tube to be of any practical use.

In the course of the years several tubes of an entirely different type have been developed, tubes whose operation is based upon the finite transit time of the electrons. The most important of these "velocity-modulated" tubes are magnetrons, klystrons and travelling-wave tubes. These are the tubes that have been mainly responsible for opening up the decimetric, centimetric and even the millimetric wave-ranges for radio engineering. Most of these tubes contain one or more cavity resonators, so that in principle each type is suitable for use at only one frequency. There are, it is true, various methods of varying this frequency to a slight extent [2]), but only over a small range (a few %). By the use of external cavity resonators and by very accurately adjusting the supply voltage, it is possible to extend the frequency range of klystrons and travelling-wave tubes, but none of these types can be employed as a universal tube for covering the entire frequency range up to, say, 900 Mc/s.

By contrast, the more conventional tubes (triodes, tetrodes) all operate with external oscillator circuits (e.g. cavity resonators) which can, in principle, be designed for any frequency (provided it is lower than the limit frequency of the tube) and which can be tuned as required.

There has naturally been no lack of attempts to raise the limit frequency of triodes by improvements in design. As regards tubes capable of a power output of several hundred watts, we may take as an example the TB 2.5/300 transmitting triode, described in this Review in 1949 [3]), which at 200

*) G. Diemer, K. Rodenhuis and J. G. van Wijngaarden, Philips tech. Rev. **18**, 317-324, 1956/57 (No. 11).

[1]) M. J. O. Strutt and A. van der Ziel, Philips tech. Rev. **3**, 103-111, 1938.

[2]) See, for example, Philips tech. Rev. **14**, 92, 1952/53.

[3]) E. G. Dorgelo, Philips tech. Rev. **10**, 273-281, 1948/49.

Mc/s delivers 200 W with an efficiency of about 60%. In the present article we shall describe some new developments in this field, which have led to the design of the triode TBL 2/300 (*fig. 1*). The limiting frequency of this tube has been raised to

Fig. 1. The transmitting triode TBL 2/300.

900 Mc/s. With a D.C. supply the TBL 2/300 can deliver more than 400 W at 470 Mc/s and about 150 W at 900 Mc/s [4]), with an efficiency of about 63 and 34% respectively. With A.C. supply — which is permissible in diathermy, for example — the power output is about 200 W at 470 Mc/s. Other favourable electrical properties are: good power gain and suitability for wide-band amplification with a relatively low supply voltage (2500 to 1300 V, according to the frequency).

In view of the diverse fields of application of the tube, its mechanical properties have to be taken into consideration. From an electrical point of view it is desirable to have short electrodes, small tube-capacitances, low self-inductance in the leads and short transit times. The first two requirements, calling for electrodes of small dimensions, entail heavy current densities and high specific loading, which adversely affect the tube's useful life. Lower self-inductance calls for leads with a large surface area, e.g. disc electrode leads (see below) and for a planar or a cylindrical electrode system. For short transit times the inter-electrode spacing must be small, and this threatens to conflict with the requirement of mechanical strength. It was therefore necessary to find a compromise. The fact that a favourable compromise was found is due, among other things, to the special construction of the cathode and to the use of a new material for the grid.

Description of the transmitting triode TBL 2/300

The article cited under [3]) gives a number of reasons why, from the electrical point of view as well as from the mechanical and thermal points of view, a cylindrical arrangement of the electrodes in a transmitting tube is preferable to a planar arrangement; among other things, it allows the use of a helical cathode and allows easy alignment of the electrodes. As may be seen from the cross-section in *fig. 2* and from the exploded view in *fig. 3*, a cylindrical arrangement has been adopted for the TBL 2/300. The directly heated cathode, marked *7*

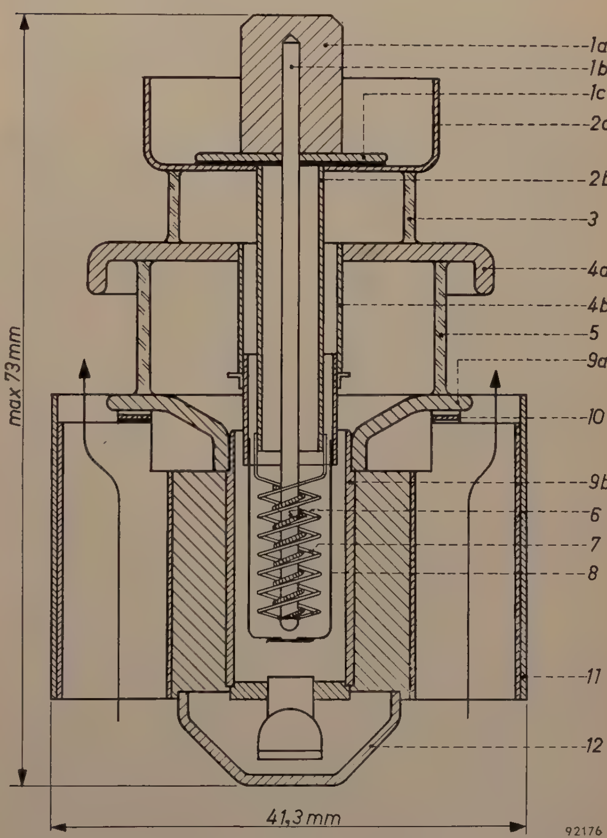


Fig. 2. Cross-section of the tube. *1a*, *2a* filament current connections. *1b*, *2b* mounting pieces for filaments *7* (two coils of thoriated tungsten wire in parallel). *1c*-*2a* shunt capacitor (sandwich seal). *3*, *5* glass insulating rings. *4a* grid disc. *4b* grid mounting tube. *6* getter (zirconium wire). *8* cage-type grid. *9a* anode disc. *9b* anode. *10* corrugated metal washer. *11* jacket around cooling fins. *12* protective cap.

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[4]) For an improved version, still in course of development, which is capable of a somewhat higher power output, see the end of this article.

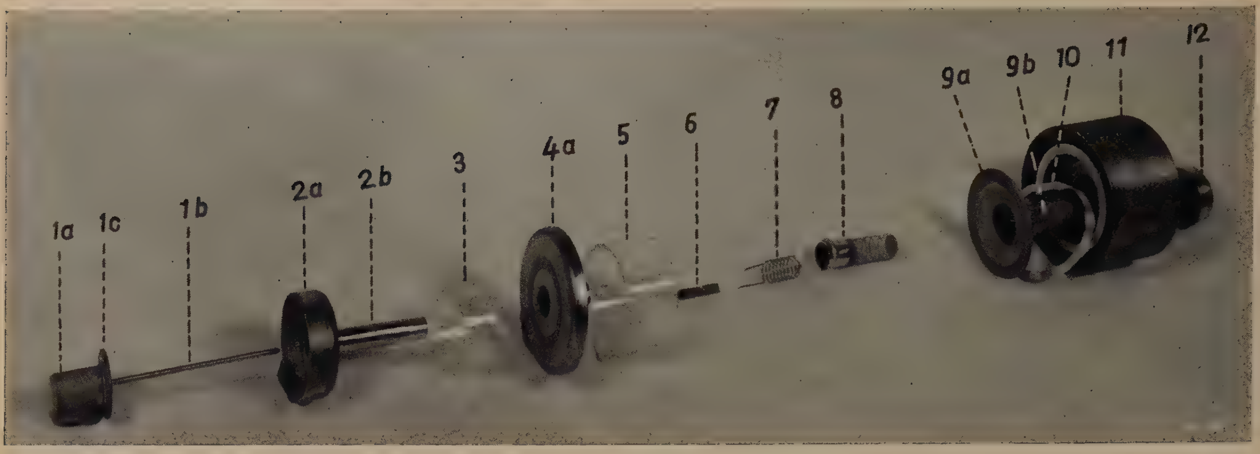
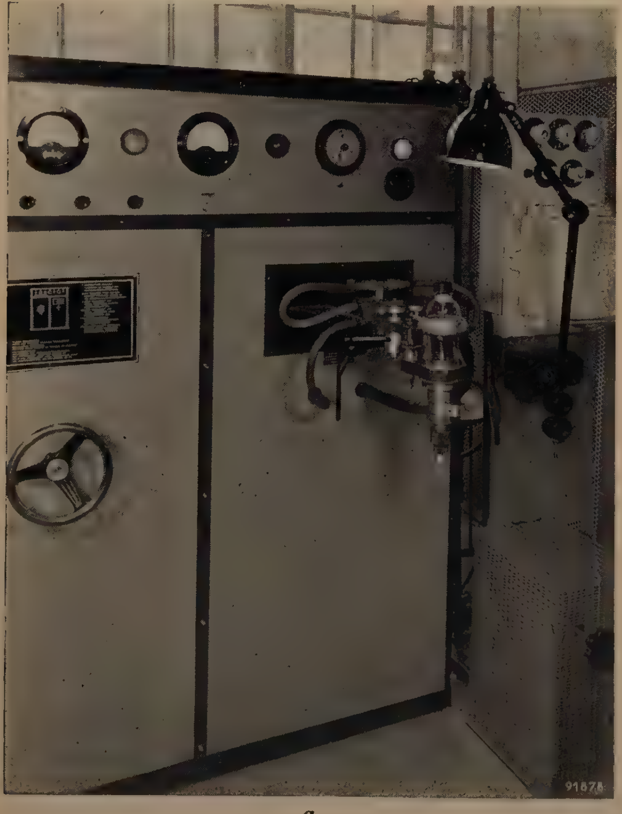


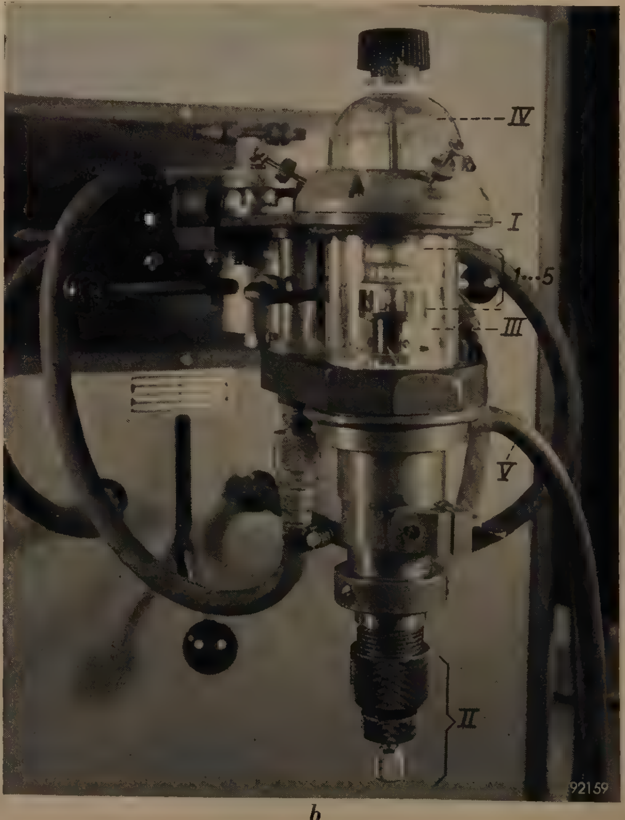
Fig. 3. Exploded view of the TBL 2/300 tube. Symbols as in fig. 2.

in both figures, consists of 2 parallel helices of thoriated tungsten (of which more later). Around the cathode are assembled the cage-type grid *8* and the anode *9b*. The metal parts *2a*, *4a* and *9a* are commonly called discs (although their shape is rather more intricate) and hence the tube is referred to as a disc-seal triode. This design allows the tube to be connected to an external coaxial system. The filament connections consist of the central contact *1a* and disc *2a*, which are connected to the filament via rod *1b* and bush *2b* respectively, both of molybdenum. The rod supports the filament and is partially wound with zirconium wire *6*, which functions as getter. The discs *1c* and *2a*, with a layer of glass between (sandwich seal) constitute a capacitor, the purpose of which will be described later.

Disc *4a* serves as the grid connection. It is



a



b

Fig. 4. *a*) High-frequency induction heater, used for sealing together the components of the TBL 2/300.
b) The sealing of components *1-5* (see fig. 3). *I* applicator coil, flat in order to concentrate the heating. *II* adjusting screws, for adjusting the height of the components. *III* glass envelope with glass cap *IV*, containing protective gas fed in by hose *V*.

insulated from discs *2a* and *9a* by rings *3* and *5*, which are of hard glass with a high melting point. The discs are of fernico — an alloy of iron, nickel and cobalt, whose coefficient of expansion is close to that of the glass. All external metal parts are silver-plated, to reduce skin-effect losses and also to ensure good contact with the external circuits.

The anode itself (*9b*) is also of fernico. Heat is dissipated via a thick-walled copper cylinder to a large number of cooling fins surrounded by a copper jacket *11*. The cooling surface is 380 cm², and the maximum dissipation is 380 W (300 W anode dissipation, 15 W grid dissipation and 65 W from the filament). Air is blown in through the cooling fins preferably in the direction of the arrows shown in fig. 2, since in that case, owing to the upper extension of the jacket *11*, the emergent air can also pass over and cool the glass ring *5*. If the incoming air is no warmer than 45 °C, an air flow of 0.45 m³ per minute is sufficient, the pressure drop across the assembly then being 24 mm water. The air current required for two tubes can be provided by a small centrifugal fan, driven by a 70 W motor. For a total dissipation of 380 W per tube the temperature of the air passing the cooling assembly rises by about 30 °C.

The jacket *11* also serves as the electrical connection for the anode. The corrugated metal washer *10* ensures good electrical contact via disc *9a*.

The exhaust stem is located at the base of the anode, and is protected by a cap *12*.

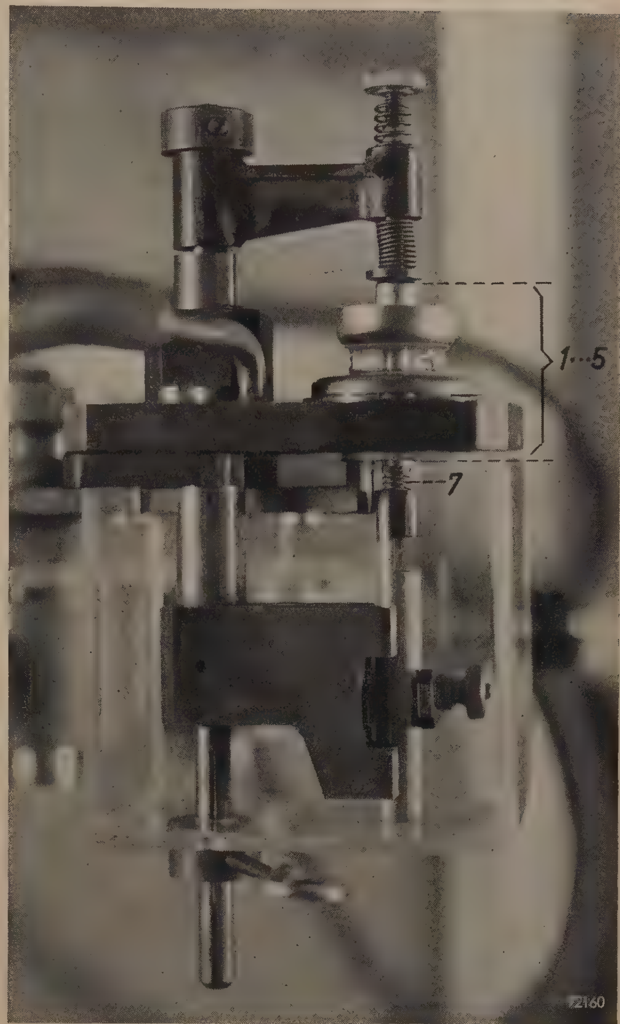


Fig. 5. The filaments *7* are brazed to the assembly *1-5* by high-frequency heating.

Manufacture

Parts *1*, *2*, *3*, *4* and *5* (fig. 3) are placed in a jig and sealed together by high-frequency heating (*fig. 4a*). A flat applicator coil *I* (fig. 4*b*) concentrates the heating in the fernico components, the height of which is accurately adjusted by means of screws *II*. The glass is softened by the radiation from the hot fernico components. All this is done in a protective gas atmosphere, for which purpose the jig is mounted in a glass cylinder *III* with a glass cap *IV*. To the assembly so produced (*1 . . 5*) the cathode filaments are now connected. *Fig. 5* shows how the filaments are brazed to bush *2b* (cf. figs. 2 and 3) by concentrated high-frequency heating. This is also done with the aid of a jig and in a protective gas. To improve their emission properties, the thoriated tungsten filaments are subsequently "carbonized", that is to say, annealed in a carbonaceous gas in order to reduce the thorium oxide. Finally, the getter is introduced.

The grid is accurately brazed concentric to the assembly by a method similar to that used for connecting the filaments. The next process is the sealing-in of the anode, the protective gas now being present only in the tube. After exhausting the tube and cutting off the stem, the cooling-fin assembly is soldered on and the external metal parts silver-plated.

The cathode

As stated, the cathode is of thoriated tungsten. In the article cited under [3]) it was explained that two objections had for a long time precluded the use of this material. The first was grid emission, caused by the thorium evaporating from the cathode and forming a deposit on the grid, and the second was the fact that tantalum, which is costly, was the only metal suitable to be used for the anode, no other metals being known with a sufficiently low gas emission to prevent poisoning of the cathode by traces of oxygen. It was not until the discovery of

the gas-absorbing properties of zirconium [5]) that the thoriated cathode could be used on a wider scale in conjunction with an anode of less costly material; graphite, for example, was sometimes used [3]). As we have seen, the anode in the TBL 2/300 is of fernico. In telecommunications, as in industrial applications, it has been found that the thoriated tungsten cathode, with zirconium as getter, has a long useful life. We shall deal with the question of grid emission presently.

In the design of a cathode for a tube required to operate at frequencies of hundreds of Mc/s, certain other difficulties arise. The first is that, owing to the transit time, the emitted electrons do not pass through the grid in exactly the right phase and some of them therefore return to the cathode. The electron bombardment so produced causes extra heating of the cathode, which can be very damaging in that it gives rise to atomization of the oxide layer. Another reason for the over-heating of the oxide cathode during emission is the poor electrical conductivity at the boundary plane between the nickel and the oxide layer. This does not occur with the thoriated tungsten cathode; moreover, this type of cathode appears to be much better able to withstand electron bombardment, even at current densities from 1 to 1.5 A/cm^2. A familiar method of reducing the influence of electron bombardment, at frequencies where the transit-time effect is noticeable, is to make the filament voltage lower than at lower frequencies. In the TBL 2/300 the filament voltage need only be slightly lowered. In wide frequency ranges it may even remain constant. The following values are specified:

Frequency	Filament voltage
$\leq$ 600 Mc/s	3.4 V
600-750 Mc/s	3.3 V
750-900 Mc/s	3.2 V

The second difficulty is connected with the requirement that the cathode — where no special measures are adopted — must be very short compared with the shortest wavelength λ_{min} at which the tube is required to operate. To illustrate this, *fig. 6* shows a schematic cross-section of the tube with its associated circuits. Coaxial resonant systems are connected to the cathode K, the grid C and the anode A; the tube is tuned by shifting the shorting-pistons p-p and q-q. We shall now consider the situation in which the distances of p and q to the end m of the diode proper are both $\frac{1}{4}\lambda_{min}$ (approx. 8 cm at 900 Mc/s).

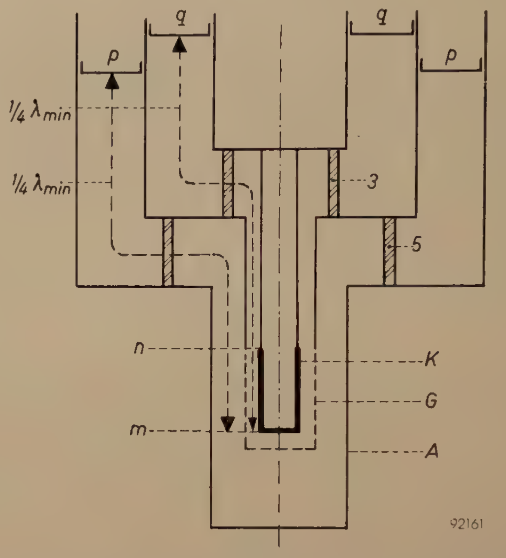


Fig. 6. Schematic cross-section of TBL 2/300 and coaxial resonant system. K cathode. G grid. A anode. 3, 5 glass rings. p-p annular shorting-piston for anode circuit. q-q annular shorting-piston for grid circuit. The triode proper lies between m and n. The distances mp and mq are $\lambda/4$.

Fig. 7 shows how the high-frequency anode-grid voltage V_{ag} and cathode-grid voltage V_{kg} vary from the end m to the shorting-pistons p and q. In fig. 7a it is assumed that the cathode is a small tube (directly or indirectly heated). The length mn of the triode proper is about $\frac{1}{4}$ of the length $mp = mq = \frac{1}{4}\lambda_{min}$, and consequently the alternating potential differences V_{ag} and V_{kg} along the anode and cathode respectively are small. However, a thin-walled tube, as would be needed for a cathode, cannot be drawn from thoriated tungsten. In practice, therefore, we are obliged to adopt a (directly heated) wire cathode. If a very high filament current is to be avoided, the wire must be fairly thin and long. For this reason a helical form is to be preferred (fig. 7b). In this case, however, ultra-high frequency operation is impossible because if the length of the filament is about $\frac{1}{2}\lambda_{min}$, a voltage node will occur in the middle of the cathode. At that point V_{kg} will be zero and thus there will be no net anode alternating current, while on either side of the node the anode currents will be in anti-phase; the total anode alternating current will then be almost zero and the tube will be unable to operate.

[5]) J. H. de Boer and J. D. Fast, Rec. Trav. chim. Pays-Bas 55, 459-467, 1936; J. D. Fast, Philips tech. Rev. 5, 217-221, 1940.

The solution of this difficulty is to take two helices, connected in parallel and each with a length of 7.5 cm ($\approx \frac{1}{4}\lambda_{\min}$), and to shunt them with a capacitor C of such a capacitance that the end m (fig. 7c) is at almost the same high-frequency potential as the end n. The result is that V_{kg} is practically constant over the entire length of the cathode, so that the cathode at high frequencies is almost an equipotential surface. The form of V_{kg} shown in fig. 7c was measured on an enlarged model (designed by J. M. van Hofweegen) with a correspondingly larger wave length.

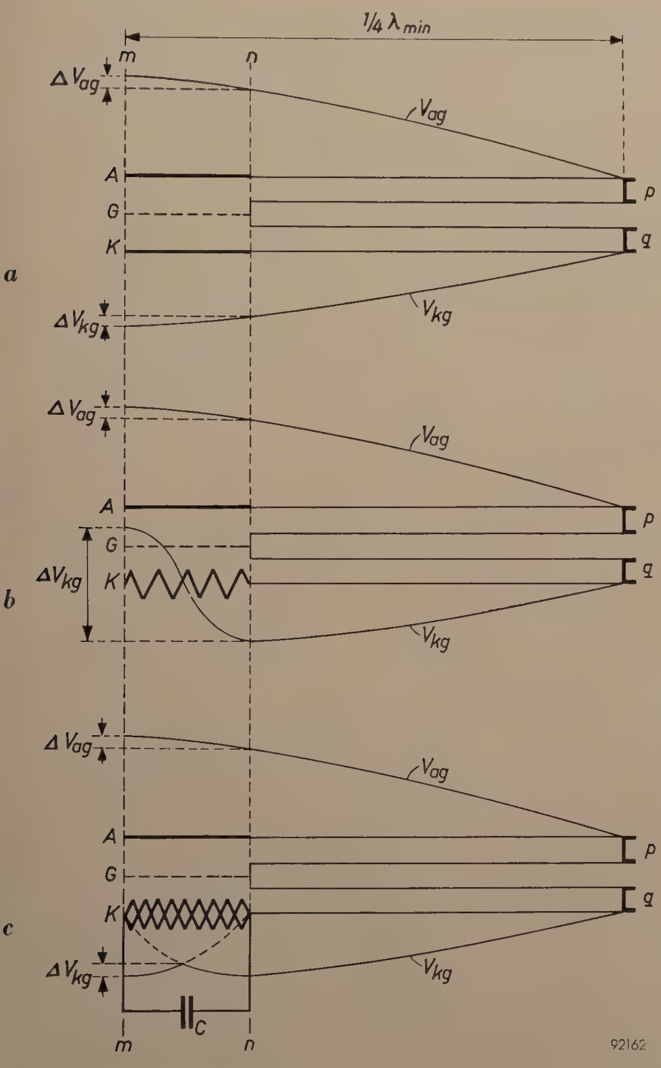


Fig. 7. K cathode, G grid and A anode of triode (schematic) showing the variation of the alternating voltages V_{ag} between anode and grid, and V_{kg} between cathode and grid, along the length of the anode and cathode respectively. ΔV_{ag} and ΔV_{kg} potential differences between the ends of these electrodes. p, q shorting-pistons (cf. fig. 6). $mp = mq = \frac{1}{4}\lambda_{\min}$.
a) Cylindrical cathode. ΔV_{ag} and ΔV_{kg} are small if the electrodes are short compared with $\frac{1}{4}\lambda$. The cathode is then an almost equipotential surface.
b) Helical wire cathode, with wire length $\frac{1}{2}\lambda$. The two halves are in anti-phase and therefore work in opposition.
c) The cathode consists of two coils, each $\lambda/4$ in length, connected in parallel and shunted by the capacitor C. The potential difference ΔV_{kg} is about as small as in (*a*).

Fig. 8 shows the connections to the cathode (the two helical filaments are drawn side by side for clarity). Capacitor C is formed by the sandwich seal already mentioned (fig. 2), the capacitance of which is about 50 pF. At a filament voltage of 3.4 V the filament current is about 19 A.

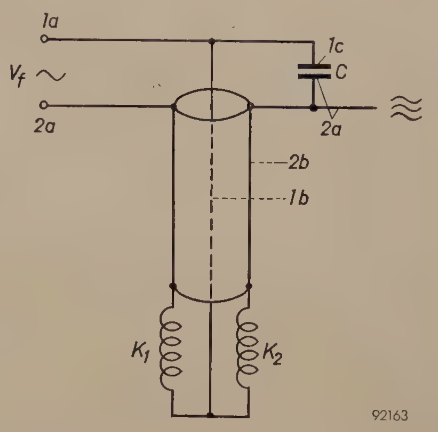


Fig. 8. The two coiled filaments K_1 and K_2 (shown side by side for clarity) and the capacitor C. For *1a*, *1b*, *1c*, *2a* and *2b*, see figs. 2 and 3. The filament voltage V_f is applied between *1a* and *2a*. *2a* is also the connection for the high-frequency current.

The grid

The cage-type grid consists of a large number of thin rods interconnected by 5 rings. The grid thus adequately approximates electrically to a conducting, entirely enclosed, surface, which is necessary in order to produce the V_{kg} distribution shown in fig. 7c.

An old problem encountered with transmitting tubes is grid emission. Substances evaporating from the cathode (in this case thorium) can, if they settle on the grid, cause the grid to emit electrons quite profusely. These electrons constitute a current in opposition to the normal grid current. If the negative grid voltage is produced by means of a leak resistor, the drop in the total grid current can result in instability. The risk of instability is particularly great if the tube is suddenly fully loaded after the filament has been switched on for a long period without any potential on the anode: during such a period a great deal of cathode dust will have settled on the grid, and when the load is applied the grid becomes hot and hence strongly emissive.

Several substances, such as zirconium oxide and platinum are known to have a low emission when used as grid material. These substances have been thoroughly tested in experimental TBL 2/300 tubes, both in new tubes and in tubes that had already operated 1000 hours with the high specific grid load of 15 W/cm². The results are set out in *fig. 9*, in which the specific grid emission current is logarith-

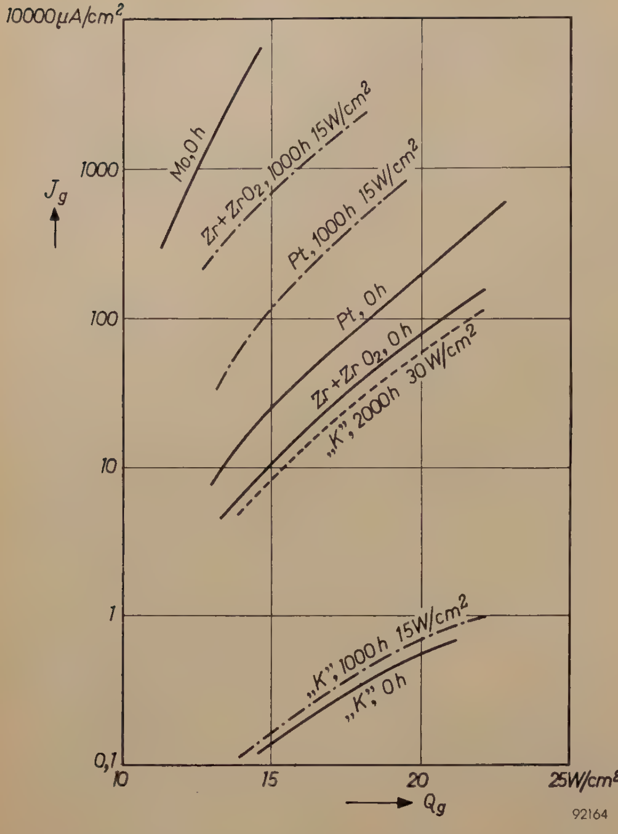
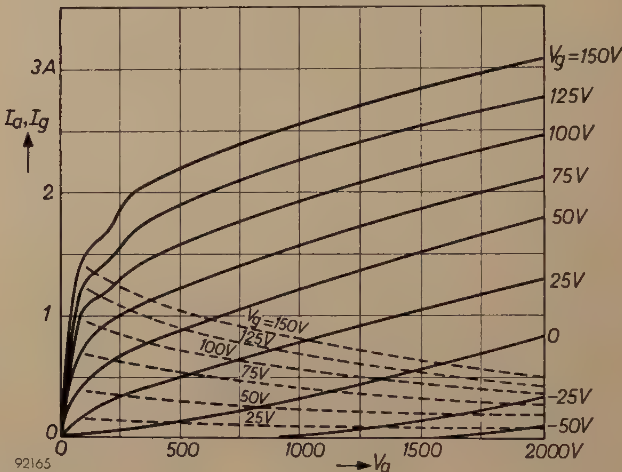


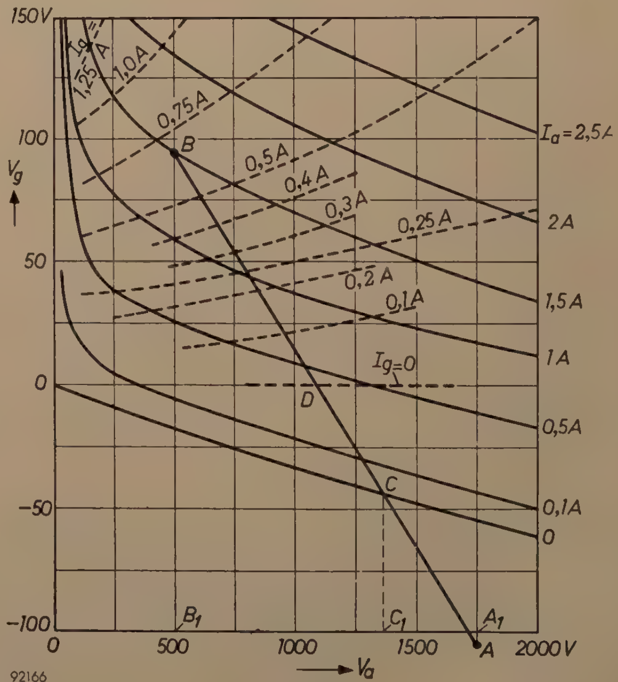
Fig. 9. Specific grid emission J_g (on a logarithmic scale) of experimental TBL 2/300 tubes, with grids of different materials as a function of specific grid dissipation Q_g. The fully-drawn curves apply to new tubes. The dot-dash curves are measurements made after 1000 hours at $Q_g = 15$ W/cm². The dashed curve refers to K material, measured after 2000 hours at $Q_g = 30$ W/cm². *Mo* = molybdenum. *Pt* = platinum on molybdenum. $ZrO_2 + Zr$ = zirconium oxide and zirconium on molybdenum. "*K*" = K material.

mically plotted as a function of specific grid load. It can be seen that of all materials tested, molybdenum is the least suitable, having by far the strongest emission. Platinum, when fresh (plated on a molybdenum core), is appreciably better, and zirconium oxide (mixed with zirconium and also coated on Mo) is slightly better still. After 1000 hours at 15 W/cm², however, the emission from the latter material has become greater than that of Pt and approaches fairly closely the emission of uncoated Mo.

A substantial improvement is obtained with a new material, referred to as "K material". Its emission is about 1/100 of that of ZrO_2 + Zr or of Pt when fresh, and after 1000 hours at 15 W/cm² it shows hardly any increase. Not until after 2000 hours at 30 W/cm² (four times higher than the specified load) does the emission approach that of fresh ZrO_2 + Zr. Owing to its great ductility, the use of K material for the grids makes the tube well able to withstand shocks and vibrations. This is an important point, having regard to the uses of the TBL 2/300 in mobile equipment and in industry. This favourable combination of electrical and mechanical properties prompted the use of K material for the grid of the TBL 2/300. The geometry of the electrodes is such that the specific grid dissipation during normal operation lies far below 15 W/cm². The ultimate limiting power loading of the grid, i.e. the loading at which the grid is immediately destroyed, lies at about 60 W/cm². The wide margin between this limiting value and the normal loading of the grid is



a



b

Fig. 10. Static characteristics of the TBL 2/300.
a) Anode current I_a (full) and grid current I_g (dashed) as a function of anode voltage V_a, with grid voltage V_g as the running parameter.
b) V_g as a function of V_a for constant I_a (full) and for constant I_g (dashed).

an important practical advantage in the adjustment of an oscillator in course of construction or development.

Electrical properties

Static characteristics

In *fig. 10a* the anode current I_a and the grid current I_g are plotted as a function of the anode voltage V_a, with the grid voltage V_g as the running parameter. Fig. 10*b*, which is derived from fig. 10*a*, represents V_g as a function of V_a; the fully-drawn curves hold for constant I_a, the dashed curves for constant I_g. This diagram has the advantage that the working line is straight, which simplifies the calculations for the biassing of the tube.

As may be derived from fig. 10*a*, the slope S is approximately 18 mA/V and the amplification factor μ about 32.

Use in oscillator circuits

Extensive measurements and life tests (several thousands of hours) have been carried out on many tubes of type TBL 2/300 in different oscillator circuits. One of these oscillators operates at 840 Mc/s: some constructional details are given in *fig. 11*, the actual arrangement is shown in *fig. 12*. In *fig. 13* the frequency of this oscillator is plotted as a function of the height H of the interchangeable anode cavity resonator, for diameters D = 90 and 180 mm. Furthermore, TBL 2/300 tubes are being used in an experimental television transmitter which has been in operation at Eindhoven for some considerable time (picture 772.25 Mc/s, sound 777.75 Mc/s).

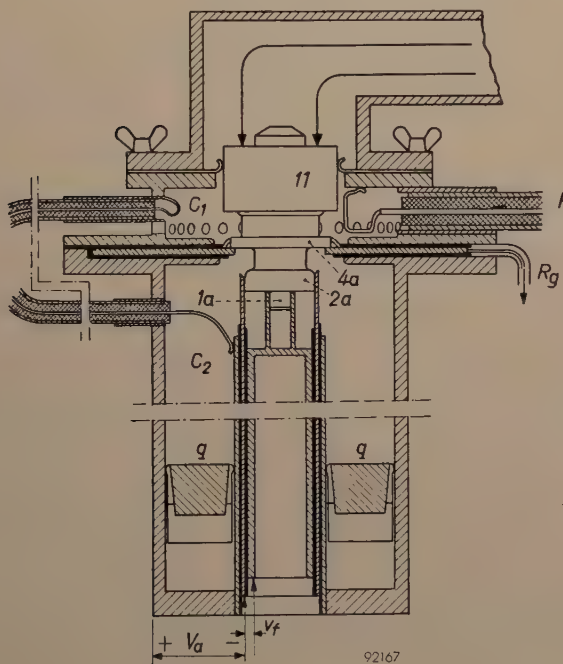


Fig. 11. Section through the coaxial system of an oscillator used for testing TBL 2/300 tubes at 840 Mc/s. *1a*, *2a* filament contacts, *4a* grid disc and *11* anode disc. C_1 interchangeable anode cavity resonator. C_2 grid cavity resonator, tuned by shorting-piston *q*. *Left*: the coaxial cable which provides for feed-back between the two cavity resonators. *Right*: the cable which takes off the output power P_o, and the connection for the grid resistor R_g. Connections for filament voltage V_f and the H.T. supply V_a are brought in from below. Air is blown in through the top.

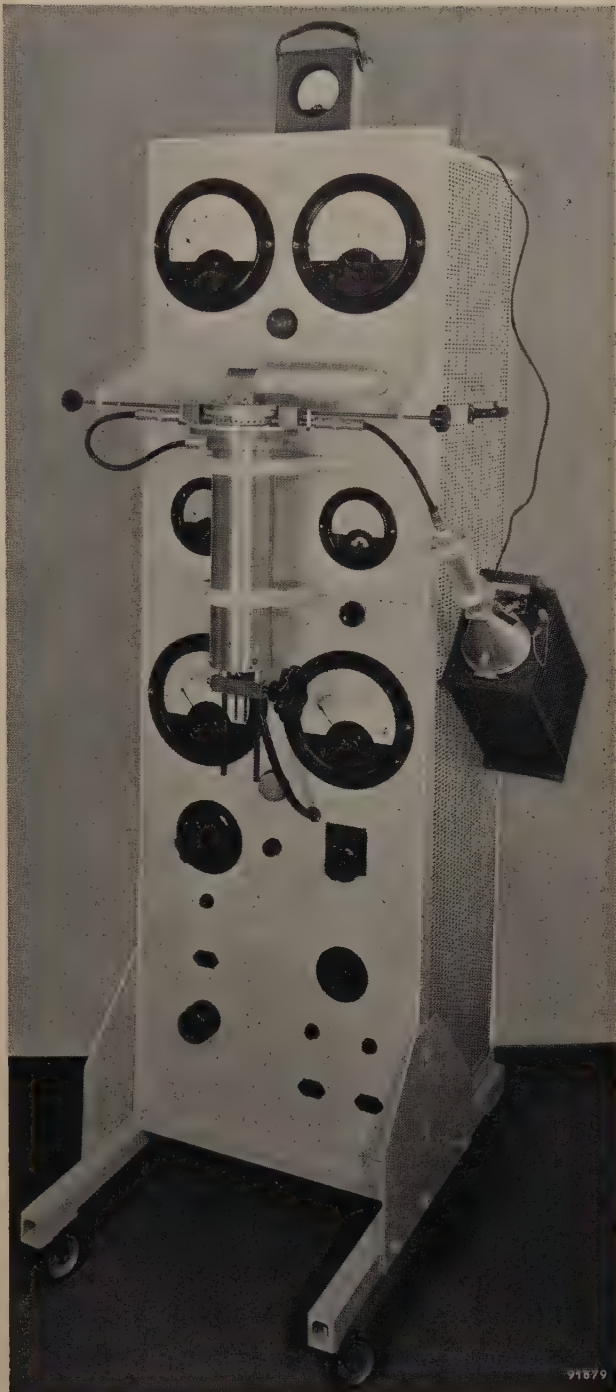


Fig. 12. Test oscillator operating at 840 Mc/s. The tube TBL 2/300 is mounted in the metal cylinder in the foreground; the load is shown on the right.

The tests have shown that the H.T. supply may permissibly be 2500 V at frequencies up to 200 Mc/s,

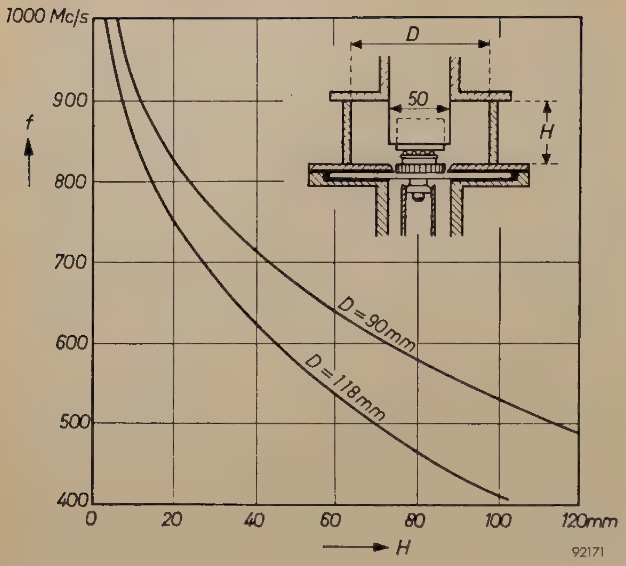


Fig. 13. The frequency f as a function of the height H of the anode cavity resonator, for two different diameters D. Inset: schematic cross-section of cavity resonator (cf. fig. 11).

but that it must be lowered according as the frequency rises (to 1300 V at 900 Mc/s) in view of dielectric losses in the glass. Partly as a result of this, the maximum power output P_0 falls from 475 W at 200 Mc/s to some 150 W at 900 Mc/s. *Table I* gives the values measured for normal operation and the maximum values; see also *fig. 14*.

With regard to the grid dissipation, it should be added that apart from the dissipation P_g of about 6 W caused by electron bombardment, heat is also generated in the grid rods owing to the skin effect. The contribution which this makes to the total grid dissipation is, in proportion, quite considerable, being about 6 W at 470 Mc/s and about 8 W at 900 Mc/s. The grid may thus have altogether about $6 + 8 = 14$ W to dissipate. The grid surface area being 2 cm², the total specific grid load is 7 W/cm², which is far below the specific load of 15 W/cm² at which the K material has been life-tested, and even further below the ultimate limit of 60 W/cm². (These values do not include the (constant) radiation heating of the grid by the filament.)

As already remarked, it is often permissible in diathermy (and also in industrial high-frequency heating) to operate the tube on alternating voltage. This saves the costs and electrical losses entailed by the use of a rectifier and a smoothing filter. Fed by alternating voltage of 1900 V r.m.s. and a mean anode current of 166 mA, the tube consumes a power of $(\pi/2\sqrt{2}) \times 1900 \times 0.166 = 350$ W; at a frequency of 460 Mc/s, the power output is then 227 W, the efficiency being 65%. Of this output a part is lost in the tuned circuit. That part can amount

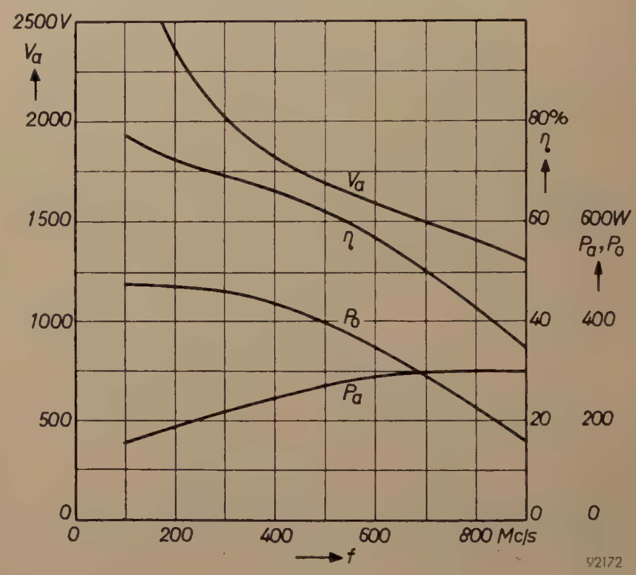


Fig. 14. Maximum permissible H.T. voltage V_a, maximum permissible dissipation P_a, power output P_o and efficiency η of an oscillating TBL 2/300 tube, as a function of frequency f.

Table I. Voltages, currents, powers and efficiency of TBL 2/300 tubes in an oscillator circuit. The values between brackets are the maximum permissible values.

Frequency (Mc/s)	175		470		900	
Wavelength (cm)	172		64		33	
Filament voltage (V)	3.4		3.4		3.2	
Anode supply voltage (V)	2500	(2500)	1750	(1750)	1300	(1300)
Anode direct current (mA)	260	(400)	380	(400)	350	(400)
Grid D.C. voltage (V)	—200	(—300)	—105	(—300)	—60	(—300)
Grid A.C. voltage (peak) (V)	275		190		—	
Grid direct current (mA)	100	(120)	100	(120)	100	(120)
Input power P_i (W)	650	(1000)	665	(700)	455	(520)
Anode dissipation P_a (W)	175	(300)	260	(300)	300	(300)
Grid dissipation P_g (W)	~6	(15)	~6	(15)	~6	(15)
Power output P_o (W)	475		405		155	
Efficiency P_o/P_i (%)	73		61		34	

to about $\frac{1}{3}$, so that about 150 W useful output remains. In diathermy and heating applications, the load is not usually continuous. The tube, which goes on oscillating when the load is removed, then takes a high grid current, which increases from, say, 65 to 95 mA, while the supply voltage increases from 1900 to 1950 V. Even in these conditions, however, the tube life was found to be satisfactory.

Power gain and bandwidth

The power gain obtainable with the TBL 2/300 at 470 Mc/s is about 15 with grounded cathode and about 5 with grounded grid.

The tube capacitances are:

Anode-grid:	C_{ag} = approx. 4	pF
Anode-cathode:	C_{ak} = approx. 0.12	pF
Grid-cathode:	C_{gk} = approx. 9	pF

For wide-band amplification it is important that C_{ag} should be small, as follows from the expression for the bandwidth B:

$$B = \frac{1}{2\pi R_a C_{ag}}.$$

In this expression R_a is the load resistance (the ratio of the alternating voltage of the anode to the fundamental of the anode current). With C_{ag} = 4 pF and R_a = 2000 Ω, the bandwidth is 20 Mc/s, which is more than adequate for all existing television systems and can also accommodate a large number of telegraphy and telephony channels.

For the power gain G_k in the grounded cathode arrangement we may write:

$$G_k = \frac{P_o}{P_{ig}} = \frac{\frac{1}{2}V_{a1}I_{a1}}{\frac{1}{2}V_{g1}I_{g1}}.$$

P_{ig} is here the input power to be amplified, applied between grid and cathode, V_{a1}, I_{a1}, V_{g1} and I_{g1} represent the peak values of the fundamentals of anode voltage, anode current, grid voltage and grid current, respectively.

By way of example we shall take a case in which the frequency is 470 Mc/s and the maximum permissible anode supply voltage 1750 V. Half of the selected load line (AB) is shown in fig. 10*b*. The centre A of the load line lies at V_a = 1750 V, V_g = —105 V; end B lies at $I_{a\,max}$ = 1.5 A. The maximum grid current $I_{g\,max}$ is 0.7 A, the minimum anode voltage $V_{a\,min}$ is 500 V. The amplitude V_{a1} of the anode alternating voltage is thus 1750 — 500 = 1250 V.

The amplitude I_{a1} of the fundamental of the anode alternating current may be found by first determining the "conduction angle" $2\Theta_a$: the part of the period in which anode current flows, i.e. when the tube is conducting, is $2\Theta_a/2\pi$ (*fig. 15a*). It follows from fig. 15*a* and *b* that:

$$\cos\Theta_a = \frac{A_1C_1}{A_1B_1}.$$

According to fig. 10*b* this is equal to AC/AB, the value of which can be found from this figure to be

$$\cos\Theta_a = \frac{AC}{AB} = 0.325,$$

so that

$$\Theta_a = 72°.$$

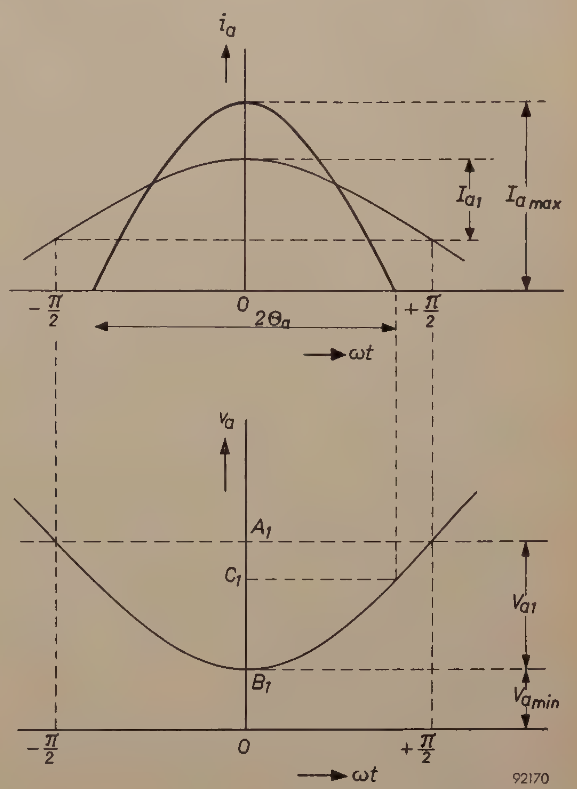


Fig. 15. *a*) Anode current i_a, (*b*) anode voltage v_a of an oscillating tube, as functions of ωt (ω = angular frequency, t = time). $2\Theta_a$ = conduction angle. Thin curve in (*a*): the sum of the fundamental of i_a (amplitude I_{a1}) and the D.C. component.

From the conduction angle we can derive the ratio $I_{a1}/I_{a\,max}$ [6]); for Θ_a = 72°, the value of $I_{a1}/I_{a\,max}$ is 0.43, so that

$$I_{a1} = 0.43 \times 1.5 = 0.65 \text{ A}.$$

With this we find for the anode resistance $R_a = V_{a1}/I_{a1}$ = 1250/0.65 = 1930 Ω (in the foregoing this was rounded off to 2000 Ω), and for the output power P_o:

$$P_o = \tfrac{1}{2} \times 1250 \times 0.65 = 405 \text{ W}.$$

V_{g1} (the difference between the ordinates of B and A in fig. 10*b*) is seen to be 200 V. For half the conduction angle Θ_g of the grid current we may write:

$$\cos\Theta_g = \frac{AD}{AB} = 0.52,$$

hence

$$\Theta_g = 58°.$$

[6]) J. P. Heyboer, Transmitting Valves, Philips Technical Library 1951, fig. 19, p. 38.

The corresponding value of $I_{g1}/I_{g\,max}$ is

$$\frac{I_{g1}}{I_{g\,max}} = 0.38\,,$$

so that

$$I_{g1} = 0.38 \times 0.70 = 0.27 \text{ A}$$

and

$$P_{ig} = \tfrac{1}{2} \times 200 \times 0.27 = 27 \text{ W}.$$

The power gain is therefore:

$$G_k = \frac{405}{27} = 15\,.$$

In grounded-grid arrangement the power gain G_g is:

$$G_g = \frac{P_o + P_d}{P_{ig} + P_d}\,,$$

in which P_d is the power directly transferred from input to output, equal to $\frac{1}{2} V_{g1} I_{a1}$. In the above example $P_d = 65$ W. Thus

$$G_g = \frac{405+65}{27+65} = 5.1.$$

Ceramic version of the tube

Finally, a few words about the latest version of the TBL 2/300, which is still in course of development. In this version the glass rings *3* and *5* (see figs. 2 and 3) have been replaced by ceramic rings. The ceramic material has an appreciably lower loss factor tan δ than the best types of hard glass suitable for fusion to fernico. Consequently, the supply voltage does not have to be lowered so much as the frequency rises, which means that the tube has a higher power output at the highest frequencies.

The ceramic-metal seal was an initial difficulty. A satisfactory ceramic-metal seal evolved by Radioröhrenfabrik Valvo in Hamburg will be described in a subsequent article in this Review.

Summary. The TBL 2/300 transmitting tube for frequencies up to 900 Mc/s is a disc-seal triode with a directly heated cathode of thoriated tungsten, a cage-type grid and an air-cooled anode. The cathode consists of two helical filaments connected in parallel, each with a wire length of about $^1/_4$ of the shortest wavelength and shunted by a capacitor, the capacitance of which (50 pF) is such that at high frequencies the cathode is almost equipotential. The capacitor is formed by a so-called sandwich seal. The grid is made of a new material ("K material"), which has extremely low emission properties, even after the tube has operated for a long period with high grid dissipation; this material also has good mechanical strength.

The slope of the tube is about 18 mA/V, the amplification factor about 32. In oscillator circuits it delivers a power of 405 W at 470 Mc/s, and 155 W at 900 Mc/s, with an efficiency of 61% and 34% respectively. The power gain is about 15 with grounded cathode and about 5 with grounded grid (both at 470 Mc/s). Owing to its low grid-anode capacitance (about 4 pF), the tube still amplifies efficiently at bandwidths up to 20 Mc/s.

A new version in course of development, in which a ceramic is used instead of glass for the insulating rings, has a somewhat higher output.

CENTRELESS GRINDING OF CERAMIC SLEEVES

Ceramic sleeves of various types and sizes are used on a large scale in the electronics industry. The photograph shows such sleeves undergoing centreless grinding down to a certain external diameter. A circular vibratory hopper (foreground) feeds the sleeves via a metal tube to the grinding wheel and pressure roller.

A TRANSISTOR HEARING AID

by P. BLOM and P. BOXMAN.

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Some time ago a short report appeared in this Review on the transistor hearing-aid type KL 5500. A more detailed description of this apparatus illustrates clearly the great advantages resulting from the use of transistors.

The entry of the transistor into electronic engineering has opened up entirely new possibilities. The most outstanding advantages of the transistor over thermionic valves are its small dimensions and low power consumption, the latter mainly because no filament current is required. Moreover, the power can be supplied by a source of very low voltage. This is particularly advantageous where the source consists of dry batteries, since the energy (the number of watt hours) is supplied much more cheaply by a battery of a few volts than by a battery of some tens of volts. Furthermore, practice has already shown that, in general, transistors may be expected to have a longer life than valves.

Small dimensions and low battery costs are points of especial importance where hearing aids are concerned. It is not surprising, therefore, that the first practical application of transistors on a large scale has been in hearing aids, particularly since what is required is amplification at audio frequencies and relatively low power outputs, which is precisely the field of application for which transistors were first manufactured on a commercial basis. The transistors in question are nevertheless capable of supplying a higher output power than is economically possible with the subminiature valves used in valve hearing aids.

Transistors offer certain other advantages which make them particularly suitable for hearing aids. In the circuit with a common emitter, which is the circuit mostly employed at low frequencies, the impedances involved are relatively low [1]). Even in a very compact construction there is therefore nothing to fear from stray capacitance coupling: the stray capacitances form high impedances carrying negligible currents. What is more, transistors show no microphonic effect; the measures normally needed to combat this effect can therefore be dispensed with, which again makes for compactness.

With the Philips transistor hearing aid described here (type KL 5500) [2]), the aim has been to help the largest possible number of users. Accordingly this is still the hearing aid with the widest field of application. Two other types are also being manufactured: type KL 5600, which corresponds substantially to KL 5500 but is smaller (with the sacrifice of some of its possibilities and entailing higher battery costs) and the even smaller type KL 5700, which is in a certain sense a de luxe model, combining minimum dimensions with high quality. In *fig. 1* the three hearing aids are shown side by side.

Requirements to be satisfied by a hearing aid

Speech intelligibility, which is of course the most important criterion for the usefulness of a hearing aid, is a problem which has been solved in modern instruments to the satisfaction of a wide circle of the hard of hearing. Although new measures to improve speech intelligibility are continually being developed — particularly as regards special types of deafness — more and more importance is now being attached to requirements of a more secondary nature concerned with the need to hear comfortably without great effort. For all types of deafness, comfortable hearing is determined in the first place by a favourable signal-to-noise ratio, and in the second place by low non-linear distortion (by non-linear distortion, the instrument itself adds new frequencies to the received signal). Noise in hearing aids is produced partly by the circuit itself and partly by friction between parts of clothing near the apparatus or between clothing and the case of the apparatus (case noise).

The more detailed requirements to be satisfied by a hearing aid depend to a large extent upon the nature of the patient's deafness. A hearing aid capable of meeting the needs of a wide circle of users must therefore possess considerable flexibility.

[1]) For the three principle transistor configurations, viz. the circuits with common emitter, common base and common collector, and for a survey of some of their fundamental properties, see for example J. P. Beijersbergen, M. Beun and J. te Winkel, The junction transistor as a network element at low frequencies, I. Characteristics and *h* parameters, Philips tech. Rev. **19**, 15-27, 1957/58 (No. 1).

[2]) Briefly described in Philips tech. Rev. **17**, 315, 1955/56.

Fig. 1. The three Philips transistor hearing aids, types KL 5500, KL 5600 and KL 5700 (from left to right). The one on the left, which has the widest field of application, is discussed in this article.

In most cases a maximum acoustic gain of 55 dB appears to be more than sufficient. Of this, depending upon the degree of his deafness and upon the intensity of sound in the microphone, the patient can use what he needs by varying a volume control. In cases of severe deafness, however, it is desirable to be able to boost the maximum acoustic gain up to, say, 65 dB.

Furthermore, for the amplification to be effective it should be possible to produce a sufficiently large sound pressure in the ear without this being associated with serious distortion. The earphones commonly used can readily produce the required pressure, provided the output transistor in the hearing aid can supply the power. In most cases, a maximum available output power of one milliwatt is more than enough for driving ordinary earphones. In cases of very severe deafness, however, it may be desirable to increase the output to as much as 10 milliwatts. The same higher output may also be needed when bone-conduction earphones are used. With an earphone of this type, which is fixed behind the ear by means of a headpiece, the sound vibrations are conducted to the organ of hearing via the bones of the skull. For this purpose, more power is needed than for the normal conduction of sound via the air in the auditory passage.

For some patients, particularly for sufferers from conduction deafness, an amplification independent of the amplitude of the input signal is suitable. The amount of the amplification will differ for different patients: where a high amplification is needed, a large maximum power output must, of course, also be available.

There are also patients, however, for whom it would be quite wrong to have an amplification independent of the amplitude of the input signal. Such patients include those who can only hear sounds whose intensity lies above a certain level, but for whom the threshold of pain ("acoustic trauma") is about the same as for persons with normal hearing. This situation is found in the case of sufferers from regression deafness [3]). For such patients the output power of the hearing aid must be prevented from exceeding the value corresponding to the threshold of pain, as the amplitude of the signal in the microphone increases. This means that the amplification and the maximum available power must be separately adjustable.

Apart from the amplification as a function of the amplitude of the received signal, the amplification as a function of the frequency is of considerable importance. The curve illustrating this dependency, is called the response curve, or "fidelity characteristic", of the hearing aid. A flat curve is not usually required. What is aimed at is an agreeable tone quality, but the meaning of "agreeable" in this context depends upon the nature of the hearing defect and upon the opinion of the patient. This does not exclude cases where the patient must, as it were, reassemble his "library" of sounds from a spectrum which, though he may find it troublesome, perhaps, in the beginning, he finally comes to accept as true. In order to be able to meet all these diverse re-

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[3]) The properties of the human ear and the various forms of deafness are briefly discussed in an article by P. Blom: An electronic hearing aid, Philips tech. Rev. 15, 37-48, 1953/54, which describes a valve hearing aid.

quirements, it must be possible to regulate the instrument's response curve.

The hearing aid KL 5500

The amplification and power outputs mentioned above can be attained economically with valve hearing aids only by using batteries of a relatively large volume, and this would make the hearing aid too large to be acceptable nowadays. If the size of such a valve instrument is kept acceptably small by the use of miniature batteries, the battery costs are exorbitant, since small batteries are much less efficient than large ones. The properties of the transistor make it possible to solve the problem. The Philips hearing aid type KL 5500 contains four transistors (three of type OC 70 and one, the output transistor, of type OC 71), all connected in the common-emitter configuration.

The battery holder is designed for a carbon-zinc rod-type battery, consisting of a single cell which supplies a voltage of 1.5 V. The output obtained is more than 1 mW, which is quite sufficient in all except extreme cases of deafness.

Since the cell used is relatively large (*fig. 2*), the battery costs are extremely low, amounting to about

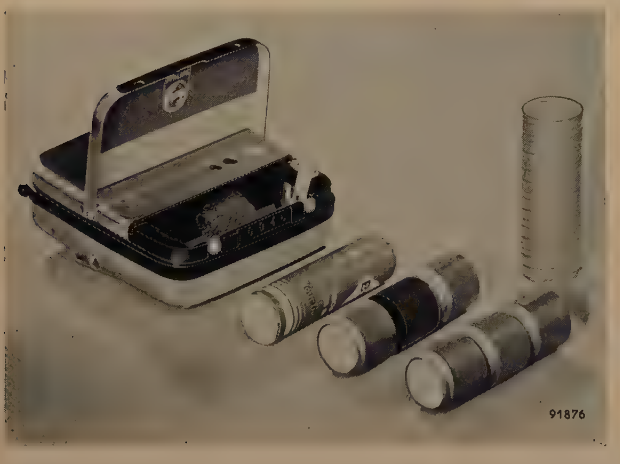

Fig. 2. The battery holder of the KL 5500 hearing aid, with the three types of batteries that may be used: a Leclanché dry cell (1.5 V), two mercury cells with filler piece (2.6 V) or 3 mercury cells (3.9 V).

one tenth of the costs of a comparable valve hearing aid. A larger power output and more amplification become available if the battery voltage is increased, which can be done by using two or three mercury cells of 1.3 V each (fig. 2). The available output power is then 4 and 10 mW respectively. This, however, considerably increases the battery costs. In the first place, current consumption increases in proportion to the voltage; the replacement of the carbon-zinc cell by three mercury cells means, therefore, that the current consumption increases roughly by a factor of 3. Thus, although the number of mA-hours of a mercury cell is about 1.5 times larger than that of a carbon-zinc cell, about six mercury cells will be used up for every one carbon-zinc cell. In the second place a mercury cell costs much more than a carbon-zinc cell (prices differ from one country to another). In order to save battery costs in cases where a supply voltage of about 4 V is needed, an ordinary $4\frac{1}{2}$ V flat torch battery may be connected to the instrument with a plug.

To produce a simple circuit with a flat, reproducible characteristic (to which corrections, if required, can readily be applied), the successive amplifier stages are *RC* coupled (*fig. 3a*). No transformers are used, thus saving space, weight and costs. The moving-iron microphone is connected directly to the first amplifier stage, and the earphone (also of the moving-iron type) is directly connected to the output transistor. The volume is controlled by a potentiometer R_3 after the second amplifier stage. To prevent the threshold of pain from being exceeded, the maximum power of the output stage can be limited by a variable resistor R_1 in the collector circuit of that stage (this will be dealt with later). A multi-position switch, comprising S_1, S_2 and S_3 in fig. 3, serves for switching the battery on and off and for attenuating the low and high tones. The microphone can be switched over to a listening coil, which enables signals to be picked up inductively from the field of an exterior coil, such as that of a telephone receiver. The listening coil may also be used in combination with a loop circuit fitted in theatres and other buildings for the benefit of the hard of hearing [4]).

Details of the amplifier

The functioning of the circuit can best be understood by considering the D.C. and A.C. circuits separately. The D.C. circuit is shown in fig. 3*b*; it is obtained from fig. 3*a* by the omission of all branches containing capacitors. The A.C. circuit is represented in simplified form in fig. 3*c*, in which all capacitors acting as short-circuits to the alternating signal current are considered as ideal short-sircuits and the internal resistance of the supply battery is neglected. Accordingly, resistor R_5 has also been omitted in fig. 3*b* and *c*. (R_5, together with C_5, provide decoupling, that is, they prevent alternating voltages, which appear across the internal resistance of the battery,

[4]) See the article quoted in note [3]), page 42.

from being fed back into the preceding amplifier stages.)

The transistors in the first three amplifier stages are wired in the same way, both for A.C. and D.C. The resistors R_b and R_c in each of these stages serve for the D.C. biassing. With $R_b = 2.2\ \mathrm{k\Omega}$ and $R_c =$ 39 kΩ, the battery voltage being 1.3 V, the operating point *P* shown in *fig. 4* is obtained. This point is chosen very low in the family of characteristics (small I_c), the object being to conserve the battery by a minimum consumption of current (the collector current is about 0.4 mA, the base current about 10 μA).

Since resistor R_b is not connected directly to the battery, but via the resistor R_c, there is not only a signal (A.C.) feedback but also a biassing (D.C.) feedback. The biassing feedback is the more important, since this makes the collector direct current (I_c) less sensitive to temperature changes, which in turn prevents the amplification from varying appreciably with temperature changes of a few degrees centigrade. We shall now consider this subject in more detail.

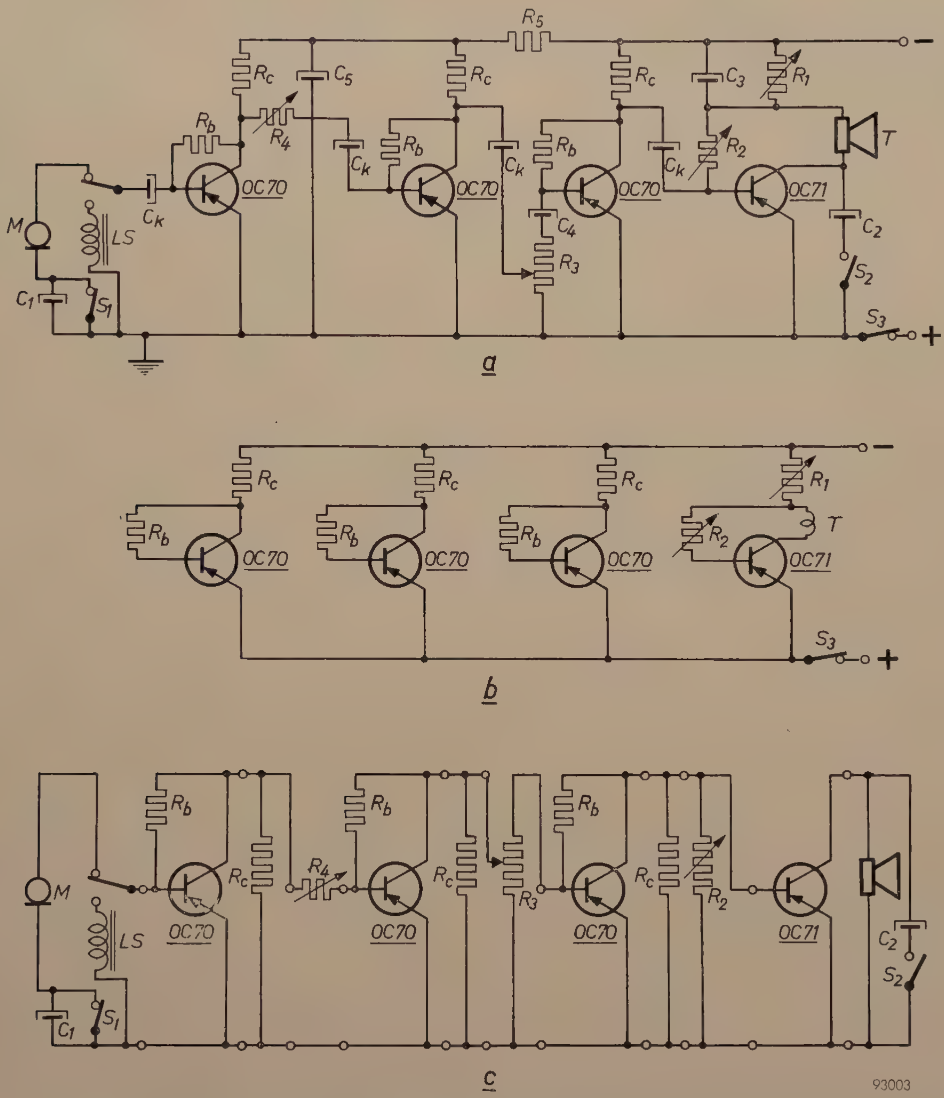

Fig. 3. *a*) Complete circuit diagram of hearing aid KL 5500. *b*) Direct-current circuit. *c*) Alternating-current circuit, drawn as a cascade arrangement of fourpoles, terminated at each end by a twopole.

M microphone; *LS* listening coil; S_1, S_2 and S_3 switches, for attenuating the low and high tones, and for switching the apparatus on and off. S_1, S_2 and S_3 are combined in a four-position switch. In the first position, S_3 only is open (apparatus switched off), in the second position all contacts are closed (high tones attenuated), in the third position S_2 is open (all tones amplified normally) and in the fourth position S_1 is also open (low tones attenuated).

Stabilizing the amplification against temperature variations

It can be seen in fig. 4 that the characteristics for constant base current I_b are almost horizontal. We may therefore write, to a good approximation [5]),

$$I_c = I'_{c0} + \alpha' I_b. \quad \ldots \ldots \quad (1)$$

The two terms of which I_c is composed are indicated in fig. 4; α', which is the current amplification factor, is a constant in so far as the lines for constant I_b are equidistant. What does not appear from fig. 4 is that I'_{c0} is strongly dependent on the temperature: for every 10 °C increase in temperature, I'_{c0} is approximately trebled [6]). The current amplification factor, on the other hand, is only slightly sensitive to temperature variations. If I_b is constant, changes in I'_{c0} will entail the same changes in I_c (see (1)). Since according to fig. 4, I'_{c0} and $\alpha' I_b$ in the first three amplifier stages are of the same order of magnitude, the appreciable relative changes of I'_{c0} with temperature variations of a few degrees will have a considerable effect on I_c. If R_b were connected directly (not via R_c) to the battery,

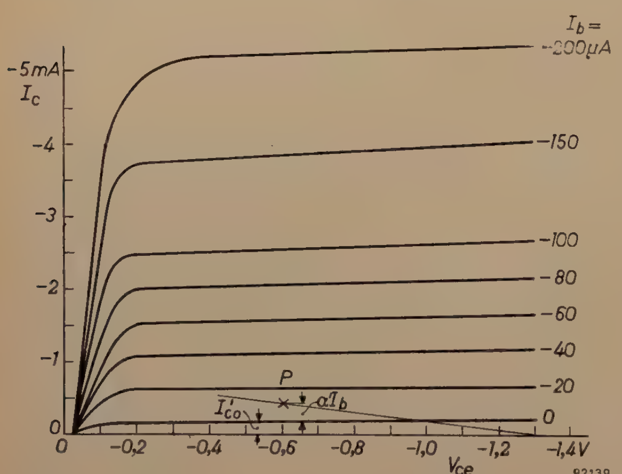

Fig. 4. Collector current I_c as a function of the voltage V_{ce} between collector and emitter, with the base current I_b as the running parameter, plotted for transistor OC 70, as used in the first three amplifier stages. The direct-current operating point is chosen at point *P*.

I_b would indeed be constant. This may be seen from *fig. 5a* which is the D.C. circuit for such an amplifier stage: $I_b = V_0/R_b$, which is constant (the voltage of approx. 0.1 V between base and emitter is negligible compared with the battery voltage V_0). However, in the circuit with negative feedback (fig. 3*b*), I_b depends on I_c. If I_c rises with rising temperature, owing to an increase in I'_{c0}, the voltage across R_b will decrease as a result of the increasing voltage drop across R_c. For this reason the current I_b, and

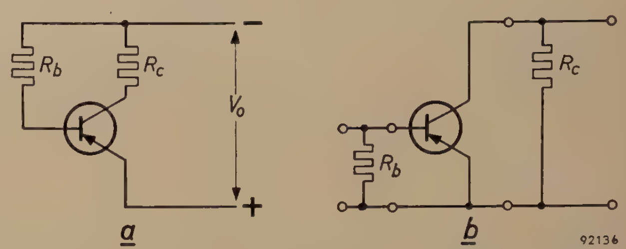

Fig. 5. *a*) The direct-current circuit of an amplifier stage, for the case that the resistors R_b of fig. 3*a* are connected directly to the battery; (*b*) alternating-current circuit.

hence $\alpha' I_b$, will also decrease, and therefore I_c will change less than I'_{c0} (see (1)). In this way a measure of stabilization of I_c is achieved.

For a D.C. circuit as in fig. 5*a*, the circuit for A.C. would be as shown in fig. 5*b*. It can be seen that now the transistor by itself occurs as a fourpole (shunted by resistors). Since the output of each transistor would then be virtually short-circuited by the input of the following transistor, the behaviour of the transistor as a fourpole is very simple, for we may take for the input resistance and the current amplification the values obtaining with short-circuited output (see pp. 23-25 and figs. 11 and 12 of the article quoted in [1])). This input resistance decreases sharply with increasing I_c [7]). If I_c rises with rising temperature, a larger portion of the output current of any stage will therefore flow into the base of the following transistor, and the output current of that transistor will increase in the same proportion. The total gain of the four stages would consequently drift by 7 to 8 dB per 10 °C, if it were not for the feedback actually applied, which reduces the temperature variations of I_c by a factor which in the present case is 2.5. If we wish to ascertain to what extent this will reduce the influence of temperature on the amplification, we must bear in mind that the stages in fig. 3 are rather more intricate than those in fig. 5, not only for direct current, but also for alternating current. In fig. 3*c* it can be seen that the transistors actually form fourpoles only when considered *together* with the resistors R_b. This makes the situation somewhat

[5]) The fact that the characteristics do show a certain slope, small as it may be for the scale values used here, makes itself perceptible only if R_c is much larger than the 2.2 kΩ used here. In that case a small change in I_c is associated with a large change in V_{ce}, and formula (1) can then no longer be used.

[6]) An article on temperature effects in transistors is shortly to be published in this Review. *Ed.*

[7]) See, for example, J. P. Beijersbergen, M. Beun and J. te Winkel, The junction transistor as a network element at low frequencies, II. Equivalent circuits and dependence of *h* parameters on operating point, Philips tech. Rev. **19**, 98-105, 1957/58 (No. 3), particularly page 104, in which the input resistance with output short-circuited is denoted h^e_{11}.

complicated. It will be enough here to report that the total gain of the hearing aid under discussion increases by only 2 to 3 dB per 10 °C rise in temperature.

Although the signal negative feedback reduces amplification per stage, it makes the amplification less dependent upon the properties of the individual transistors. Since individual transistors of the same type show a considerable spread in their properties. such stabilization is very welcome: the transistors in the first three stages can now be replaced without any re-adjustments being necessary.

Another adverse influence on the amplification is the fact that the coupling resistors R_c constitute parasitic loads on the transistors. The advantages of simple circuitry without transformers, and with stabilization against temperature variations, entail quite a considerable sacrifice of gain in the pre-amplifier. The theoretical maximum power gain of an OC 70 transistor — i.e. the power gain with ideal matching at the input and the output — is about 36 dB at the operating point considered. In the actual circuit, however, the first two amplifier stages produce only 19 dB each and the third 20 dB. The final stage produces 22 dB, making an overall (electrical) gain of about 80 dB.

The output stage

The small electromagnetic earphone is connected directly in the collector circuit of the output transistor OC 71. The variable resistor R_1 (fig. 3*a* and *b*), used for limiting the power output, is normally set at zero. It is moreover bypassed by a capacitor C_3, so that no signal feedback occurs and the output transistor forms, in itself, a fourpole (fig. 3*c*). The output characteristics of this transistor (with the input current I_b as the running parameter) are shown in *fig. 6*.

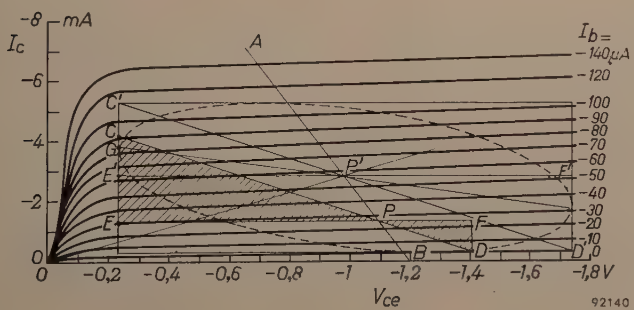

Fig. 6. Output characteristics of the output transistor OC 71. *B* indicates the battery voltage (taken as 1.2 V). The slope of *AB* corresponds to the D.C. resistance of the earphone (75 Ω). With a sinusoidal voltage across the load impedance (the earphone) an ellipse is drawn around the operating point; the diagonal of the coordinate rectangle tangential to this ellipse has a slope that corresponds to the value of the load impedance in ohms. To determine the most favourable operating point and load impedance, only this diagonal needs to be considered.

Biassing. The earphone has a D.C. resistance of 75 Ω. If $R_1 = 0$, the operating point then lies on the line *AB* (fig. 6) of slope corresponding to 75 Ω, running through the point *B* which represents the battery voltage. By varying the base direct current with R_2 (fig. 3*a* and *b*), the operating point can be shifted along *AB*. The position of the operating point is chosen with a view to conserving the battery, that is to say it is chosen as low as is compatible with the power required to be available at the earphone. This power, as already stated, is 1 mW for normal purposes. This is the power we wish to have available when using a battery consisting of one cell, that is, at a battery voltage of about 1.2 V (to which the voltage drops when the battery is run down). The family of characteristics is limited on the left (the curves drop sharply) and underneath (since the collector current cannot change sign). Imagining, for the sake of simplicity, the earphone impedance to be replaced by a pure resistance, and assuming that *P* is the operating point, we can draw through *P* a load line *CD*. The area of the triangle *PDF*, which is the smallest of the two hatched triangles *PDF* and *PCE*, is then a measure of the available useful power, i.e. the power that the transistor can deliver without serious distortion. If the operating point is moved up along *AB* by raising the base current, the areas of the two triangles will then approach each other; they become equal when CD has moved to *C'D'*. If the slope of *CD*, i.e. the value of the load, is chosen such that the available useful power is exactly 1 mW in the situation corresponding to *C'D'*, we have then found the most economical operating point at the given voltage. In our case the required load is found to be about 300 Ω. The slope of *CD* in fig. 6 has been chosen in accordance with this value.

The situation in reality is complicated by the fact that the earphone constitutes a strongly inductive load. For a sinusoidal output signal of a single frequency, the output characteristic is represented by an ellipse drawn around the operating point, instead of a straight line. The diagonal, from top left to bottom right, of the coordinate rectangle tangential to this ellipse, has a slope that corresponds to the impedance of the load. If this diagonal does not extend to regions where distortion may be expected, then neither will the ellipse extend to such regions. The value of 300 Ω mentioned above is therefore the value which the impedance of the earphone (and not the purely resistive portion of this impedance) must have in order that the biassing be such as to give the most economic operating point. Of the available power only that part given

by the area of triangle $P'E'G$ is dissipated in the earphone.

Since the impedance of the earphone depends on the frequency, it can only be exactly 300 Ω for one frequency. Earphones are used which have this impedance at a frequency of 1000 c/s.

A second complication is that no definitive conclusion can be drawn from fig. 6 regarding the distortion to be expected. It is not at all evident, for instance, that serious distortion occurs if the transistor is driven to very small values of I_c. This distortion is due to the fact, already mentioned, that the input resistance of the transistor increases sharply at small values of I_c. Nevertheless, the method indicated above of determining the most economical operating point and the most favourable load impedance from fig. 6 does lead to results of practical value.

Since the current amplification factor of the OC 71 transistor may vary between 30 and 75 with individual transistors of the same type, the base current at which the most favourable operating point is obtained depends upon the transistor employed. It must therefore be possible to adjust the base current during assembly and subsequently if replacement of the output transistor should be necessary; this is the reason for making the resistor R_2 variable.

Limiting. The operating point discussed above automatically provides that, with increasing input signal, the power increases only very little from the moment that serious distortion sets in. This is due to the fact that the limiting of the output signal and the serious distortion associated with it both occur equally on both sides of the operating point (symmetrical limiting). In this way the output power is prevented from exceeding a certain upper limit, thereby providing an effective safeguard against "acoustical trauma".

The level at which the limiting becomes operative can be regulated with resistor R_1 (fig. 3*b*). The higher this resistance, the lower the collector voltage. This voltage is also across the base resistor R_2 (the slight potential difference between base and emitter is negligible) and thus the base current falls proportionately when R_1 is increased. In its turn, the collector current I_c decreases proportionately with the base current, at least as long as $I_c \gg I'_{c0}$ (see (1)). The operating point is thus shifted along the line OP' (fig. 6) towards the origin; the symmetrical cut-off is thereby maintained.

Since the amplification of the output stage is not stabilized by negative feedback, the considerable spread in the current amplification factor of individual output transistors would normally appear in full in the total gain. To prevent this happening, a variable resistor R_4 is introduced between the first and second stages (fig. 3*a* and *c*) with which the total gain can be adjusted during assembly or after the replacement of the output transistor. This also compensates for the residual spread in the characteristics of the earlier stages, still remaining in spite of negative feedback.

As regards direct current, too, there is no feedback in the output transistor when R_1 is set at zero, and therefore no stabilization of the operating point against temperature variations. This is not necessary, however, since the collector bias current I_c of the output transistor is adjusted to a much higher value than that of the transistors in the first three stages. The contribution of I'_{c0} to I_c is therefore relatively much smaller (see (1)).

If the battery voltage is doubled or trebled by using a battery consisting of two or three cells, the operating point moves along OP' away from the origin. The maximum amplitudes of current and voltage are also doubled or trebled and the available useful power is increased by a factor of 4 or 9, as the case may be. Thus, with a battery of three cells the available power is brought up to the 10 mW that is necessary for some cases of severe deafness and when bone conduction is employed. Raising the battery voltage causes an increase not only in the biassing current of the output transistor but also in that of the transistors in the first three stages. Since higher operating currents entail lower input resistance, the loss in the resistors R_c (fig. 3*c*) is lower. This causes the total gain acoustic to increase from 55 dB for one battery cell to 63 dB and 67 dB for two and three cells respectively.

With all three battery voltages the resistor R_1 allows the ear specialist to lower the maximum output power (the ceiling) continuously by an amount from 0 to 20 dB. It can be seen in fig. 3*b* that the limiting of the output is associated with a reduction in battery current, as one would wish.

Microphone, earphone and response curves

The input resistance of the first amplifier stage is relatively low, being somewhere between 1000 Ω and 1800 Ω, and thus readily permits the direct connection of a moving-iron microphone. Crystal microphones, as normally used in valve hearing aids, call for load impedances of the order of 0.1 to 0.5 MΩ. This would necessitate the use of a matching transformer, and even then less power would be delivered, with more noise. The moving-iron microphone used in the KL 5500 hearing aid has an internal resistance of 1000 Ω and is particularly suitable for

use with transistor hearing aids. Its smooth frequency characteristic facilitates the attainment of the desired overall response curve. The microphone functions as follows [8]). The vibrations of an aluminium diaphragm are transferred to an armature composed of a material of high permeability. This armature constitutes the "galvanometer" diagonal of a magnetic "Wheatstone bridge". The resistance arms are formed by air-gaps in the magnetic system, and the requisite magnetic flux is supplied by a small permanent magnet forming the other diagonal of the bridge. The magnetic flux through the armature is dependent in direction and magnitude upon its deviation from its equilibrium position. A coil fitted around the armature converts the flux variations into an alternating voltage. The system is extremely sensitive: at 1 kc/s the sensitivity is about 0.3 mV/μbar when the microphone is terminated by 1000 Ω. By means of suitably dimensioned resonant air cavities the frequency characteristic can be made fairly flat between 400 and 3000 c/s, which is the important range for speech (*fig. 7*). The consequence of these measures is that the characteristic falls more sharply outside this range, which has the advantage,

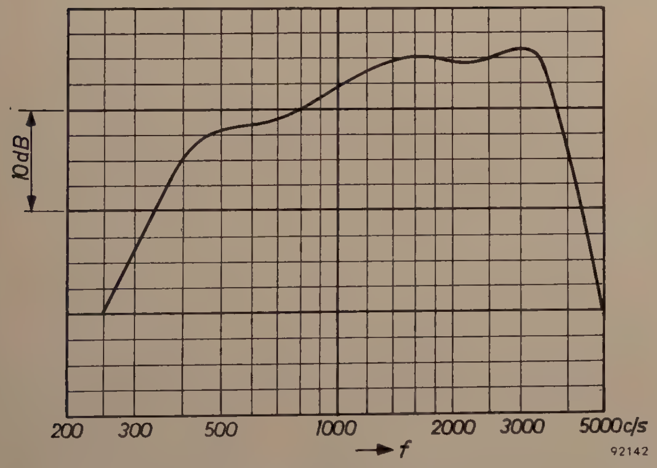

Fig. 7. Frequency characteristic of the microphone. The quantity actually plotted is the voltage across a resistor of 1000 Ω terminating the microphone, the latter being in a sound field of constant pressure.

where the lower frequencies are concerned, of very efficiently suppressing intermodulation phenomena, which may occur in the presence of "boom", in motor vehicles, for example.

The microphone casing is surrounded by two rings of a metal with a high initial permeability, the purpose of which is to shield the microphone against stray magnetic fields (attenuation by about 16 dB) and to help create a quiet background.

As regards the earphone, the patient has a choice of three types. The type Ph 1 earphone has an almost flat frequency characteristic (*fig. 8*). Unavoidable

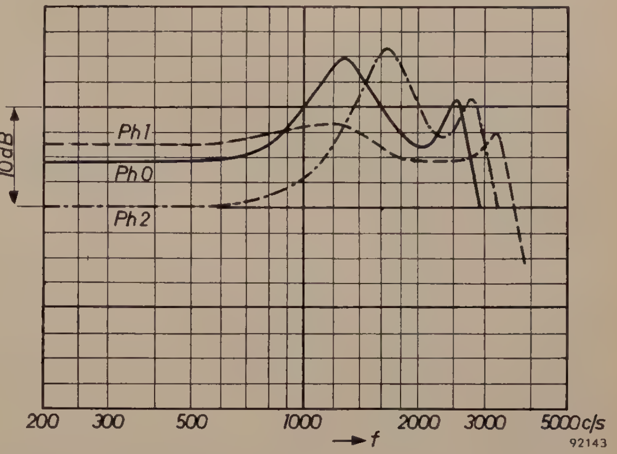

Fig. 8. Frequency characteristics of the three earphones (Ph 0, Ph 1, Ph 2) from which patients may choose. As a function of the frequency f of the constant current through the earphone, the sound pressure is plotted as measured in an artificial ear of 2 cm^3 volume in which the earphone was fixed.

resonances have been attenuated as much as possible by the introduction of damping. Fig. 8 also shows the characteristics of the two other earphones, types Ph 0 and Ph 2. In these types the resonances are attenuated to a lesser extent.

With the sum of the frequency characteristics of microphone, amplifier and earphone, an overall response curve (fidelity characteristic) is obtained as shown in *fig. 9*, using an earphone of the type Ph 1. By switching C_1 or C_2 (fig. 3), a portion of the low or

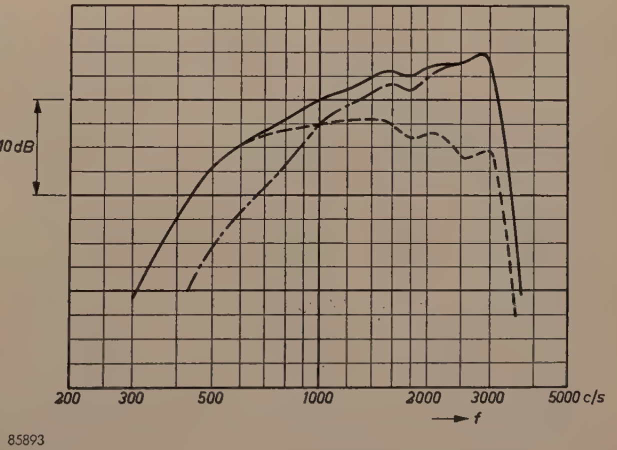

Fig. 9. Overall response curves (fidelity characteristics) of the complete hearing aid KL 5500 with earphone Ph 1, for the three positions of the control switch. The quantity plotted is the sound pressure measured in an artificial ear of 2 cm^3 volume in which the earphone was fixed, the microphone being in a field of constant pressure.

Full curve: S_1 closed, S_2 open (see fig. 3c); dashed curve: S_1 and S_2 both closed; dot-dashed curve: S_1 open, S_2 open.

[8]) For a detailed description see: B. B. Bauer, A miniature microphone for transistorized amplifiers, J. Acoust. Soc. Amer. **25**, 867-869, 1953.

high frequency range, respectively, can be cut off, producing the three curves illustrated. These curves can also be changed by the choice of earphone, so that many combinations are possible.

Case noise

The extremely low battery costs make it possible to keep this hearing aid in continuous use. This being so, it is more important than ever that the user should be able to hear with the least possible effort. Various factors are involved here, an important one being, as we have seen, that the tone quality perceived by the deaf person should be as agreeable as possible, heard against a quiet background. The most troublesome kind of background interference heard by users of hearing aids is case noise. This is caused by friction between clothing and the case of the instrument, or by friction between a piece of clothing stretched over the case and an adjacent fabric rubbing over it. Modern hearing aids are so smoothly finished, and there is so little movement of clothing with respect to the case, that the first source of case noise may, for all practical purposes, be neglected. The movement between adjacent fabrics bearing on the case, however, is many times greater in amplitude and is always present. It has the nature of "white noise"; that is to say, all frequencies in the band passed by the hearing aid are represented in almost the same intensity. Sufferers from certain types of deafness may find this extremely troublesome, and it is therefore very important to suppress this kind of interference as effectively as possible.

The vibrations produced by case noise can reach the microphone in three ways.

a) The friction may set the case and the chassis of the instrument in vibration; the vibration is transmitted to the microphone via the microphone mounting. This transmission is almost entirely determined by the natural resonance of the system consisting of the microphone (mass) and its elastic mounting (stiffness). The natural frequency can easily be kept below 100 c/s, in which case the amplitude of vibrations within the speech range remains negligible.

b) The vibrations of the case can be transmitted to air cavities inside the hearing aid. These cavities often resonate and thereby pass certain frequency ranges with extra intensity. The vibrations may possibly reach the microphone via these cavities.

c) The vibrations of the clothing material reach the microphone diaphragm via the air in the normal way.

An apparatus has been developed by Philips for making comparative measurements of the sensitivity of different hearing aids to case noise. The results of such measurements make it possible to assess objectively the measures taken to suppress interference due to case noise.

The apparatus contains an endless cotton belt driven by a small motor. The hearing aid to be tested is pressed against the moving belt, either with or without an intermediate piece of clothing fabric stretched over the case. The case noises thus produced are reproducible, and in a certain sense "standardized". The earphone of the hearing aid is fixed in an "artificial ear", and the voltage produced in the microphone of this device is fed to a voltmeter via a band-pass filter (bandwidth one third). The case noise is subsequently stopped and a standardized "acoustic" noise substituted, i.e. a noise whose vibrations reach the instrument's microphone only by the normal acoustical means, that is via the air and not by the means mentioned under *a*) and *b*) above. This acoustic noise is produced by a loudspeaker set up nearby the hearing aid and fed by a noise generator. The volume of the acoustic noise is adjusted such that the deflection of the voltmeter is the same as when the case noise was operative. A measurement is then made of the sound pressure of the acoustic noise field at the position of the hearing aid; this is done with the aid of a microphone connected via the same filter to a voltmeter which is calibrated in decibels above a threshold value of 10^{-4} dyne/cm^2. In this way the sound pressure is ascertained of the acoustic noise which, within a frequency band of one third, produces just as much interference as the standardized case noise. By repeating the measurement with different band-pass filters of one third, the entire

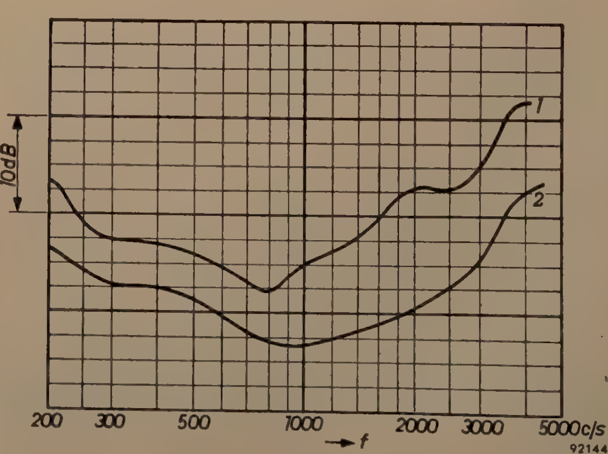

Fig. 10. Case-noise interference as a function of frequency, *1* with microphone opening partly covered, *2* with opening uncovered.

audio frequency range can be covered. The advantage of this method is that the results depend only upon the extent to which the case-noise vibrations reach the microphone of the hearing aid, and not upon the amplification or the response curve of the instrument.

The method can also be used to investigate the effect of the conditions under which the case noise is generated. As an example, *fig. 10* shows the effect of partly covering the microphone opening by vibrating fabric. With a given amplitude of vibration, the variations in air pressure in the small cavity in front of the microphone diaphragm are larger the more completely the opening is covered. It is seen from fig. 10 that when the opening is partly covered the interference is greater at all frequencies than when the opening is uncovered; in the range of about 1000 to 3000 c/s the difference is as much as 10 dB. It is important, therefore, when wearing a hearing aid, to keep the microphone opening entirely free.

The results of case-noise measurements have led to the adoption of various measures in the mechanical construction of the type KL 5500 hearing aid — and in other types too — to suppress this interference. It has been found that apparently minor modifications often have a substantial effect.

Summary. The use of transistors in the KL 5500 hearing aid has made it possible to reduce battery costs drastically and at the same time to increase the available output power and amplification. As a result, the apparatus can serve a wide circle of deaf persons. After a discussion of the various requirements to be satisfied by a hearing aid, a description is given of the amplifier, in which four transistors are used. The effects of temperature variations and of the spread in the properties of individual transistors are largely eliminated by means of negative feedback. The highly sensitive moving-iron microphone is directly coupled to the input stage, without the intermediary of an input transformer. A transformer is also superfluous for the earphone, since with transistors the maximum available power is obtained with a load having an impedance of a few hundred ohms, which is the normal impedance for electromagnetic earphones. The variable limiter prevents the maximum output power from exceeding the threshold of pain. The article concludes with some details of investigations into the interference caused by case noise.

AN APPLICATION OF TELEVISION FOR THE DISCOVERY OF VARIABLE STARS

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Variable stars, i.e. stars which vary in brightness, are of great interest in astronomy, one reason being that it is often possible to determine their distance from the earth. An electronic apparatus to help in the discovery of variable stars has been constructed at the Kapteyn Astronomical Laboratory at the University of Groningen. The apparatus makes use of techniques used in television [1]).

Variable stars may be detected by means of two photographs of the same region of the sky. The photographs are taken at different times but, apart from this, the circumstances should be as similar as possible. If the brightness [2]) of a star has changed in the lapse of time between the two exposures, the change is primarily to be detected in a difference of diameter between the photographic images of the star.

Comparison of the photographs is generally carried out by means of a "blink-microscope". With this instrument the same region of the two photographs is seen in turn in the field of vision. No change is then seen in stars having constant brightness, but variable stars appear to grow and shrink, as it were. With this procedure, however, the number of stars missed is fairly large, since it is often necessary to re-examine the plates several times before any variation in the image is noticed and not always the same stars are retrieved when a certain pair of plates be examined more than once.

Various other techniques have been devised for the search for new variable stars. One is a comparative method involving the original negative of one exposure and a positive of the other; the two are examined in conjunction, the black spots on the former being made to cover up the "holes" in the latter. The result is that stars of constant brightness become invisible, while variable stars become visible as a result of the slight differences in their two images. However, the photographic preparations that this method requires present considerable difficulty.

The new apparatus is based on the same idea, but the photographic preparations are eliminated. With the aid of the flying-spot scanner as used in television, it is possible to display a photographic negative on a CRT screen either as a positive or as a negative image, whichever is desired. The flying-spot scanner embodies a special kind of cathode-ray tube having a small bright spot with hardly any afterglow. The spot traces a raster or pattern of lines on the (flat) screen in exactly the same way as in a television picture tube. A lens projects the image of the spot onto the transparent object that is being examined; in other words, the spot is made to scan the object. The light that passes through the object is conveyed by a condenser lens to a photo-multiplier tube which delivers a signal proportional to the light passed by the object at that particular point of its surface. The signal can be used to modulate the intensity of the electron beam in a picture tube, the screen of which will accordingly display an image of the object [3]).

With the aid of a half-silvered mirror it is possible to scan two objects at the same time using one cathode-ray tube. Such an arrangement is used in the present apparatus.

Fig. 1 shows the principle of the apparatus. A half-silvered mirror M_4 and three highly polished mirrors M_1, M_2 and M_3 split the light from the type MC 13-16 cathode-ray tube K into two beams; lenses L_1 and L_2 form images of the spot on both F_1 and F_2, which are photographic plates of the same region of the night sky, of the kind referred to above. The signals from the two multiplier tubes P_1 and P_2 are electronically subtracted and the difference signal, after amplification, is employed as a picture signal for modulating picture tube B. In fact, the sign of one signal is reversed, but not that of the other; the two are then added. If each of the signals is taken separately, therefore, one will produce a negative image on the screen, and the other a positive image, as shown in *fig. 2*.

If two identically similar plates are examined in this way (care naturally being taken that the plates are so positioned that corresponding points are always scanned at the same time), the signals from the two photo-electric multiplier tubes will always be equal. Consequently the difference signal will remain zero and nothing will be seen on the screen.

[1]) J. Borgman, Dissertation, Groningen 1956.
[2]) In astronomy the term "brightness" is taken to indicate the illumination intensity produced on earth in a plane perpendicular to the line of sight to the star.

[3]) For a more detailed discussion of the flying-spot scanner, see F. H. J. van der Poel and J. J. P. Valeton, Philips tech. Rev. **15**, 221-232, 1953/54. For details of the cathode-ray tube, see A. Bril, J. de Gier and H. A. Klasens, Philips tech. Rev. **15**, 233-237, 1953/54.

Should the two plates differ in some way (e.g. if they carry the images of a star whose brightness has changed in the time between the two exposures), the picture signal will not be zero and the difference between the plates will be visible on the screen as a patch that is either lighter or darker than its surroundings. An example appears in fig. 2.

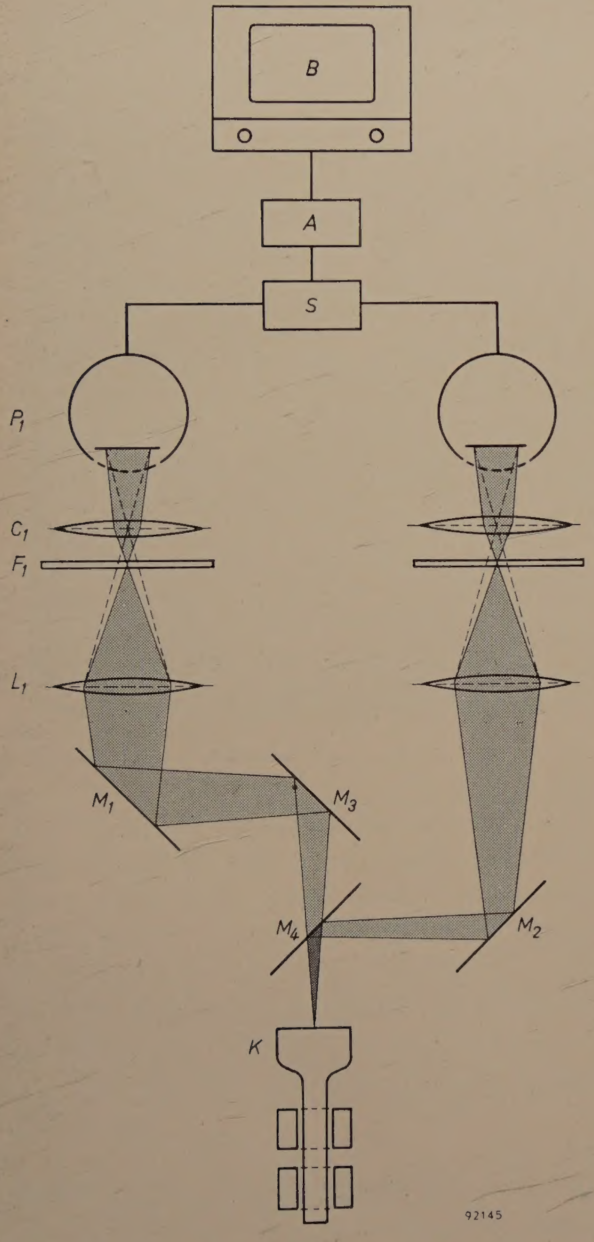

Fig. 1. The principle of the two-channel flying-spot scanner. By means of the half-silvered mirror M_4 and the highly polished mirrors M_1, M_2 and M_3, the light from the cathode-ray tube K is split into two beams. Images of the raster traced on the screen of K, reduced about ten times, are projected by L_1 and L_2 onto the two photographic plates (F_1 and F_2) to be compared. C_1 and C_2 are condenser lenses. The signals delivered by photo-electric multipliers P_1 and P_2 are subtracted. After amplification, the difference signal is made to modulate the intensity of the electronic beam of picture tube B, which forms part of a normal television set. The sweep voltages for the picture tube and for the flying-spot cathode-ray tube are synchronized. Details of the circuits may be found in the author's dissertation (see footnote [1])).

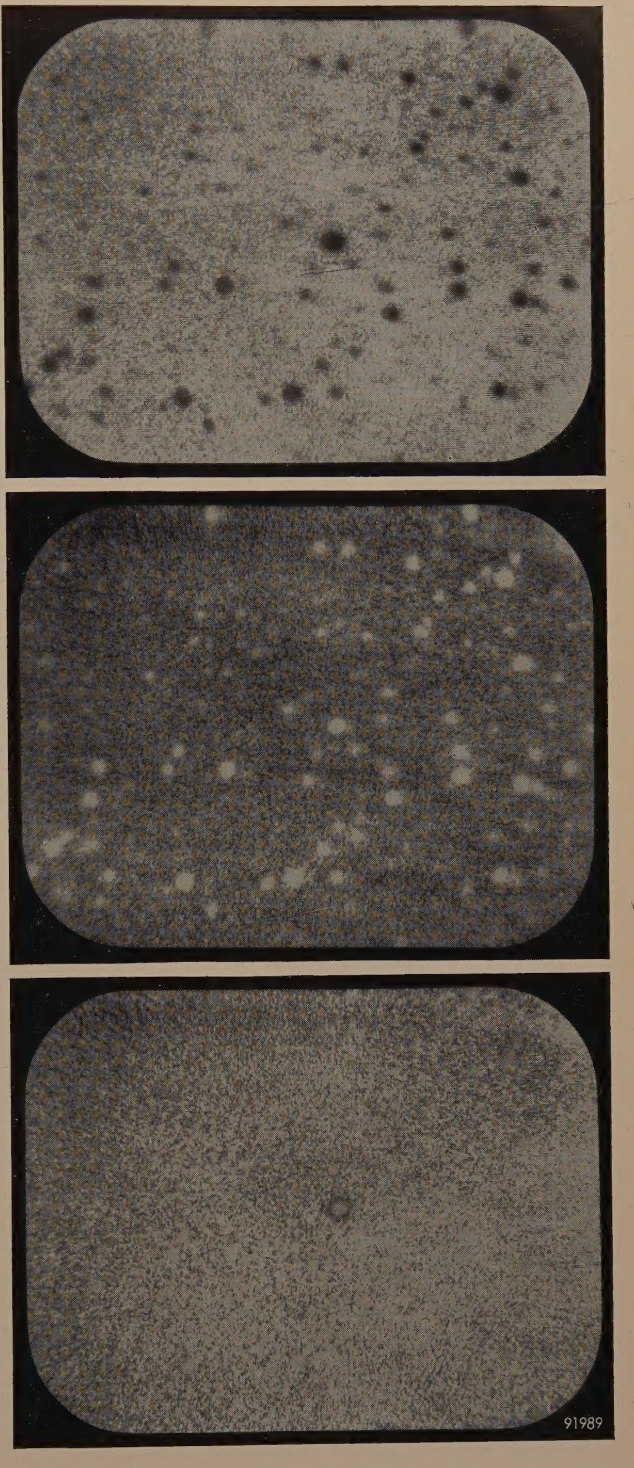

Fig. 2. Photos of the television screen taken during the scanning of a region of the plate containing a variable star. *Above:* "Negative" image of one plate. *Centre:* Reversed or "positive" image of the other plate. *Below:* The sum of the two images above. A clear case was selected in order that an unretouched photo might be shown. (Photos by Central Photographic Service of Groningen University.)

Fig. 3 is a photograph of the complete apparatus.

The chance of finding a variable star on a given pair of plates with the aid of this instrument cannot easily be expressed as a number; it depends both on the *brightness* of the star and upon the *change*

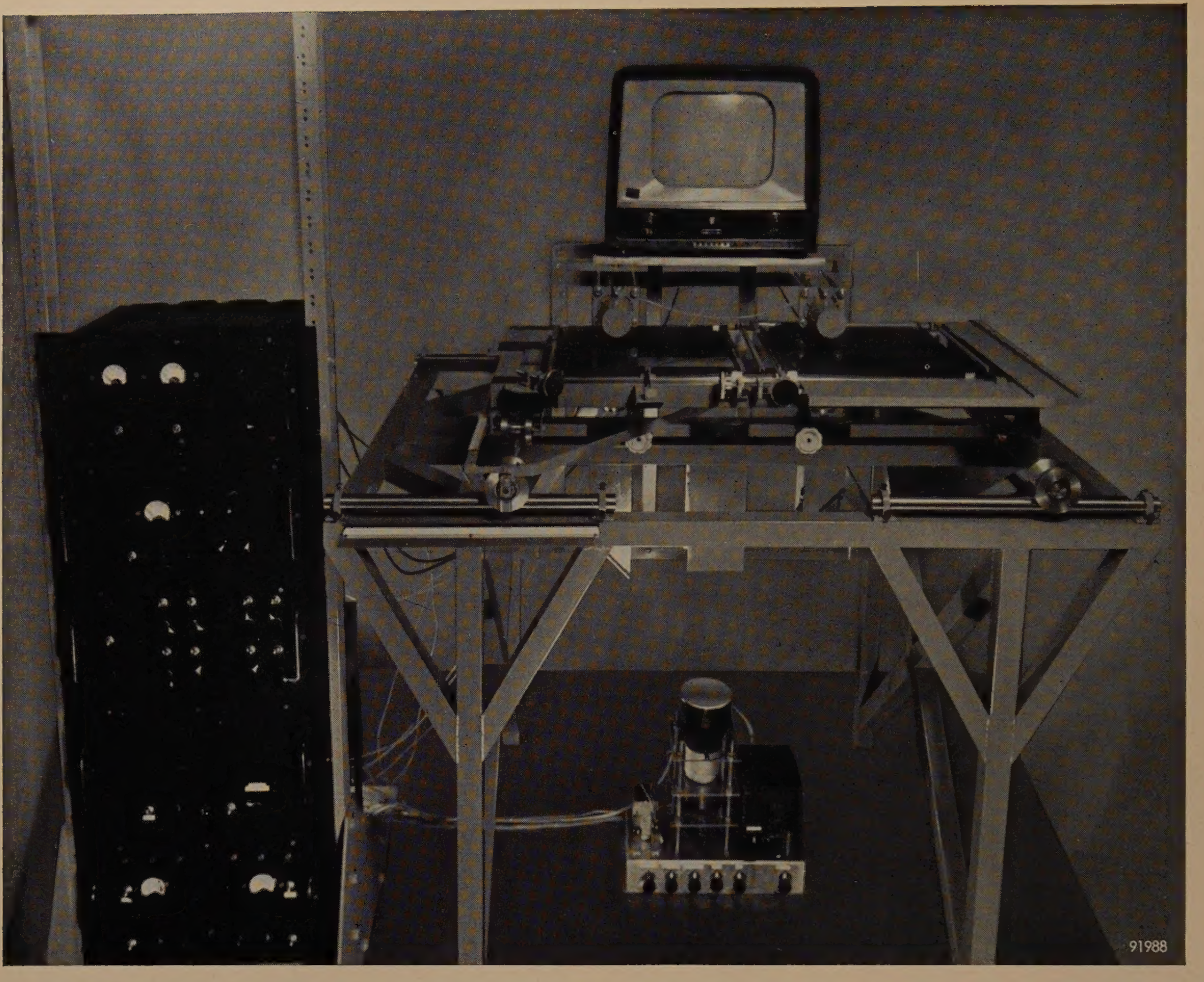

Fig. 3. The apparatus described in the text. The plate holder can be moved on rails in two directions at right-angles to each other. The two multiplier cells can be seen under the television set. The chassis carrying the cathode-ray tube and sweep generators is on the floor. The remaining electronic equipment is accommodated in the rack. (Photo by Central Photographic Service of Groningen University.)

in brightness (i.e. the difference in the photographic images). Suffice it to say that the chance is greater than when a blink-microscope is used, and that there is also considerable saving of time.

An instrument of this kind has general utility for the detection of slight differences between transparent objects. A further case in astronomy is for the detection of heavenly bodies whose positions relative to the "fixed" stars change (asteroids in particular). Outside astronomy, the instrument might be used for detecting forgeries (of bank notes, for example) and differences between air photos of the earth's surface made at different times.

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ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS BY THE STAFF OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

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2464: B. B. van Iperen: Klystrons reflex pour ondes millimétriques (Le Vide **11**, 264-266, 1956; No. 65). (Reflex klystrons for millimetre waves; in French.)

Three reflex klystrons for wavelengths of 12, 8 and 4 mm are described. These valves, which are essentially of the same construction, have a mechanical tuning range of 10-25% and deliver a continuous power output of the order of 100 mW. The measured values of the output power are found to be nearly 2/3 of those expected from the theory for all three types of valves. Using this correction factor, which is assumed to be due to the influence of space charge and transit time spread, an estimate is given of the limiting frequency for valves of the type described. It is found that the maximum frequency of 82 000 Mc/s obtained with the 4 mm valve is about one half of this limit.

2464a: F. Coeterier: Tubes à réflexions multiples (Onde électr. **36**, 917-919, Nov. 1956). (Multireflection tubes; in French.)

Some new types of multireflex klystrons are described. The basic problem of forming electron bunches and making them oscillate with constant phase around an interaction gap is solved in two ways: firstly the known method of a special retarding field, and secondly a combination of drift-tube action with a retarding field, using three interspaced gaps. Tunability is achieved by a moving metal bar between the Lecher strips forming the resonant system. If a quick sweep of the available bandwidth is required as e.g. in marine radar beacons, this metal bar can be replaced by a vibrating vane. The output is of the order of 10 W with an efficiency of 20% for both types.

2464b: J. G. van Wijngaarden: Possibilities with disc-seal triodes (Onde électr. **36**, 888-892, Nov. 1956).

With the introduction of the L-cathode in disc-seal triodes, tubes for higher frequencies than possible with normal oxide-coated cathode can be constructed. Also the H.F. output power can be considerably greater. The frequency limitations are imposed by the circuitry around the tube (especially the possibility of building a quarter-wavelength cavity around the grid-anode region) and by the transit time of the electrons. The latter is, for a given cathode-grid distance, mainly a function of the admissible current density. The H.F. output power is a function of the current density and of the admissible plate and grid dissipations. Some results obtained with a triode for 4000 Mc/s and output power of more than 20 watts at 100 Mc/s bandwidth are discussed. ₀he construction of triodes for frequencies as high as 10 000 Mc/s, with reasonable gain-bandwidth and power-bandwidth qualities, seems to be feasible.

2464c: S. Woldring: Over de ademhaling tijdens het spreken van dove kinderen (T. voor Doofstommenonderwijs **26**, 153-160, 1956, No. 4). (On the breathing of deaf children while speaking; in Dutch.)

In speech a good coordination between breathing and movement of the speech organs is important. In persons of normal hearing this coordination is achieved by listening. Investigation by means of so-termed pneumograms, taken on the chest and abdomen of normal and deaf children during rest and during speech, clearly demonstrate the lack of control of respiration in deaf children during speech. An improvement in the perception of sounds automatically brings about an improvement in speech.

2464d: H. Bremmer: Remarks on the connection between mode theory and ray theory (Nuovo Cimento (10) **4**, suppl. No. 4, 1552-1558, 1956).

By calculating a simple model for the propagation of radiowaves via the ionosphere the connection is shown between the description using the ray concept and the description with eigen functions. With the aid of the ray theory an integral formula is derived which contains the two reflexion coefficients (on earth and on ionosphere). This integral formula can be evaluated with the aid of the theorem of residues, which procedure yields the solution in terms of eigen functions. The connection between the two descriptions is due to the fact that the residues mentioned are determined by a resonance condition involving the two reflection coefficients, where the reflection coefficient on the ionosphere depends on the eigen functions of the problem.

2465: H. G. Bruijning: High-power pulse generators (T. Ned. Radiogenootschap **22**, 1-14, 1957, No. 1).

In the Philips Research Laboratory an experimental radar has been built, designed for pulses of 0.01 μs, at a repetition rate of 2000 pps. The generator had to deliver pulses of 15 kV, 15 A to the magnetron. This paper deals with the development of the pulse generator (200 kW pulses of 0.01 μs duration) and with the construction of an oscilloscope (bandwidth 400 Mc/s) specially built to be used in connection with the experimental radar mentioned above.

2466: S. Duinker: On the resolving power in the process of magnetic recording (T. Ned. Radiogenootschap **22**, 29-48, 1957, No. 1).

The recording process taking place in a thin magnetic layer situated at a certain distance in front of the recording head is analyzed if the head is magnetized by pulses superimposed upon a D.C. level, both with and without an additional A.C. biassing field. For both cases expressions are derived for the resolving power, defined as the limiting wavelength corresponding to the repetition frequency of extremely short pulses at which just once in a period the remanent magnetization inherent in the D.C. level is recorded on the tape travelling at a fixed speed. The resolution is shown to depend upon the ratio of pulse height to D.C. level, the shape of the field curve and the depth into the tape in the D.C. method, while in the A.C. method, the relative strength of the A.C. biassing field and the critical field strength of the tape are of importance also. It is demonstrated for the D.C. method that resolutions of the order of the gap length are obtainable while in the A.C. method a much smaller wavelength can be recorded.

2467: J. Bloem and F. A. Kröger: De diffusie van Cu in PbS (Chem. Weekblad **53**, 1-4, 1957, No. 1). (The diffusion of Cu in PbS; in Dutch.)

Experiments show that Cu has a strong preference for the Pb^{2+} lattice sites in PbS. At high temperatures ($T > 500$ °C) diffusion takes place mainly by a vacancy mechanism. For $T < 500$ °C, however, the lattice must be considered rigid; the diffusion of Cu occurs via the inter-lattice. Dependent on the atmosphere used (H_2 or H_2S) it is found that Cu can be made to diffuse into or out of PbS crystals at low temperatures.

2468: H. J. Oskam: Enkele aspecten van de hoogfrequente gasontlading (Ned. T. Natuurk. **23**, 1-15, 1957, No. 1). (Some aspects of the high-frequency gas discharge; in Dutch.)

The mechanism of the high-frequency gas discharge differs in a number of ways from that of the D.C. gas discharge; the former is in fact less complicated so that it is possible to set up a theory of the high-frequency discharge that agrees well with experiment. Energy transfer to the electrons is different in the two types of discharge and may be compared by the use of the so-called equivalent field. The γ-mechanism at the electrodes plays an essential role in the D.C. discharge, while in the high-frequency discharge its influence is not important. Whereas in the D.C. discharge the electrons disappear primarily as a result of the field, in the high-frequency discharge they disappear by diffusion to the walls, recombination in the gas and attachment. This is illustrated by comparing measurements of the breakdown fields in neon-argon for the D.C. case with those for the high-frequency case. The differences are explained in terms of the above remarks. By the application of high-frequency techniques it is possible to measure a number of gas-discharge quantities in a new way.

2469: J. A. Haringx: Design of corrugated diaphragms (Trans. Amer. Soc. Mech. Engrs. **79**, 55-64, 1957, No. 1.)

Three previous papers by the author set forth methods of calculating the rigidity of corrugated diaphragms, the stresses in the sheet material, and the non-linearity of the relation between load and deflection. As a further step, the introduction of a few simplifying restrictions having no fundamental effect on the problem leads to the concept of a chart giving at once the dimensions a diaphragm must have so as to conform to specific requirements. An example is included by way of illustration.